University of Victoria
Department of Physics and Astronomy

ASTRONOMY 250 LAB MANUAL

Section ____

Name ________________

July 2011

Astronomy 250 Lab Report

You MUST pass the labs to pass the course. To pass the labs you must write up your own lab and hand it in to the slot for your lab section in the box specified by your TA. Write legible full sentences in ink in a "Physics Notes" lab book. If your writing is indecipherable then type the lab report on a computer and print it so your instructor can read it. To maximize your marks you will want to follow this format. Notice that NOT all of the following components will be in every lab, so this outline is more of a guideline.

OBJECTIVE/PURPOSE Write one or two sentences about why you are doing the lab.

INTRODUCTION/THEORY Outline what the lab is about and give the historical perspective. You especially want to state what you expect the results to be from previous work. What assumptions are you making?

EQUIPMENT Often a piece of equipment is introduced which allows you to make your measurements. Describe the equipment giving pertinent details.

PROCEDURE In your own words write a brief outline of the steps you used to do the lab. It must not be a copy of the lab manual but it must say more than "See the lab manual". A reasonably knowledgeable person should be able to follow your procedure, complete the lab and get similar results.

OBSERVATIONS Some of the labs require you to sketch something astronomical so record the date, time and sky conditions on the sketch.

TABLES/MEASUREMENTS The data you measure should be put in a table on the white pages of the book with the columns labeled and underlined. Refer to the table in the procedure.

GRAPHS Sometimes we want to show how one thing is related to another and we will do that with a graph. Make sure you print a label on both axes and print a title and date on the top of the graph. The scale should be chosen so that the points fill the graph paper. Use a ruler to draw axis and other straight lines.

CALCULATIONS When you calculate an answer take note of the significant digits. If you have three digits in the divisor and three digits in the dividend then you should state three digits in the quotient. If you do the same calculation over and over (i.e. for different stars), then show one calculation and then put the other results in a table.

RESULTS The result of a lab is often a number. You must remember to quote an uncertainty for your result. You must also remember to quote the units (kilometers, light years, etc.).

QUESTIONS Usually there are a few questions at the end of the lab for you to answer. These should be answered here.

CONCLUSIONS/DISCUSSION Does your result make sense? Did you get the result you expected within the uncertainty? If not, there is some problem and you might want to check it out with your lab instructor! Discuss sources of uncertainty and how your results depend on your assumptions.

REFERENCES List the books and web sites that you used to write up this lab. Use the text but do not copy it.

EVALUATION Did you like this lab? Did you learn anything?

MARKING In general an average mark is 7 or 8 out of 10. The lab is due approximately 24 hours after you have finished it and one mark is deducted per week that a lab is late. Please hand in the lab to the box in the hall on the fourth floor. It is usually hard but not impossible to get a 10. You need to show that you are interested and to not hold back. Read the lab manual, read the text, visit a few of the suggested web sites and you will learn something to impress the marker and get a better mark.

ERRORS AND UNCERTAINTIES

One of the main purposes of science is to develop theoretical ideas/models that can reproduce and explain phenomena in the real world. Observational scientists must therefore make detailed observations and measurements of real world phenomena, which will be compared to theoretical predictions. In order to be scientifically useful, the precision and accuracy of the measurements must be understood and quantified.

In *very* broad terms, you should remember to keep track of two types of uncertainty:

1. **Errors on measurements**
   Every measured quantity will *always* have an associated uncertainy. Errors can occur, for example, because of the limitations of the measuring device, because of systematic offsets (see below), because of legitimate dispersions in the data, etc.

   Example: Suppose you are trying to measure the brightness of a star. You observe the star ten times, measure the brightness in each image, and find the average brightness from those 10 observations. However, you notice that the brightness changes slightly in each image, which means that your average is not infinitely precise. Thus, you must also quantify the spread around this average in order to understand how well the average is known and how much the brightness changes. If the star really *does* vary its brightness, this will be reflected in the spread.

2. **Errors introduced during the analysis**
   In order to relate observed quantities to physical parameters, scientists often use formulae, make assumptions, and/or rely on empirical calibrations. These can introduce additional errors/uncertainties, though they may be difficult to quantify.

   Example: Suppose you wish to use a star's brightness to determine its distance. This requires an assumption of its intrinsic brightness, which cannot be *exactly* known, though it can be modeled/estimated. It is important to understand how such assumptions could affect your analysis.

Remember, errors are an unavoidable part of science. You should always try to identify, quantify, and report your errors as accurately as possible, even if they seem unusually large. Large errors are not necessarily an indication that you have done something wrong, and may reveal something important about the data or methods.

ERROR PROPAGATION

When using measured quantities in calculations, you must properly propagate the error through to the final value. There are specific rules for error propagation (e.g. ones you may have learned in physics). For example, if you are adding two quantities, you should add their errors in quadrature (so that for two quantities, $a \pm \sigma_a$ and $b \pm \sigma_b$, the final error on the sum $a + b$ is $\sigma = \sqrt{\sigma_a^2 + \sigma_b^2}$). In astronomy, however, we sometimes deal with numbers in their logarithmic forms, or we use much more complicated equations. To keep things simple, in these complicated cases we will not use the formal error propagation rules. Instead, we will perform two calculations: one with the value we measured and one with the value we measured plus the error. The difference between the two values is then the error.

Example: Suppose you measured the distance modulus to a star to be $(m - M) = 8.3 \pm 0.2$ mag. Distance d is then given as:

$$d = 10^{(m-M+5)/5}.$$

Therefore, you compute:

$$d = 10^{(8.3+5)/5} = 457 \text{ pc}.$$

To get the uncertainty, re-calculate d using the maximum possible value of $(m - M) = 8.3 + 0.2 = 8.5$:

$$d = 10^{(8.5+5)/5} = 501 \text{ pc}.$$

Since the distance varies by $501 \text{ pc} - 457 \text{ pc} = 44$ pc, your final measurement is $d = 457 \pm 44$ pc. Note that this assumes that the errors are symmetric, i.e. that the error is the same for both $+0.2$ and -0.2 mag. This is not always the case.

RANDOM VS. SYSTEMATIC ERRORS

When thinking about errors, keep in mind the difference between accuracy and precision:

- **Accuracy** refers to how close a measurement comes to the true value. **Systematic errors** reduce accuracy.
- **Precision** refers to how many significant digits we can measure. **Random errors** reduce precision.

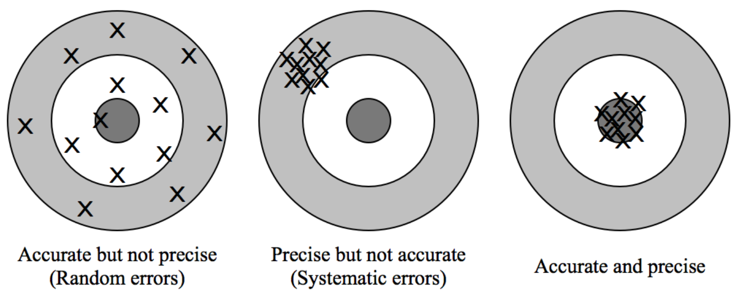


Figure 0.1: An illustration of accuracy versus precision.

A quantity can be accurate without being precise or precise without being accurate. Of course, we would like a quantity to be both accurate and precise, meaning that we would like to identify and minimize both the random and systematic errors. Figure 0.1 shows a good way to visualize the difference between accuracy and precision.

Example: Your measurement of a star's brightness requires a reference point. Suppose that in order to estimate the brightness of your target, you compare the target to another star with a known brightness that is located in the same image. However, suppose that your lab partner uses a different star for her calibration. The two of you will have *systematically* different results. You can try to estimate this systematic error by picking different stars for your calibration, or by measuring the brightness in different ways.

Often you do not combine the systematic errors together with the random errors. Instead, the systematic errors are almost always considered separately.

UNCERTAINTIES IN A SAMPLE

When we have a number of independent measurements of a quantity such as the distance to the stars in a cluster, we can average the measurements together to obtain more accuracy in the measurement of the distance to the cluster. The *average*, $\bar{x}$, is calculated from the following formula:

$$\overline{x} = \frac{\sum_{i=1}^{N} x_i}{N}.$$

Half the measurements will be larger than the mean and half will be smaller than average. How much the individual measurements scatter about the mean is measured by the *standard deviation* ($\sigma_s = \sigma_{N-1}$), sometimes called the Root-Mean-Square deviation. The standard deviation is defined by:

$$\sigma_{N-1} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2}.$$

The standard deviation measures the amount of scatter of the measurements about the mean. If the measurements differ as a result of *random* errors, 68% of the values will lie within $\pm 1\sigma$ of the mean; $\pm 2\sigma$ will include 95% of the data points.; and $\pm 3\sigma$ will include 99.7%.

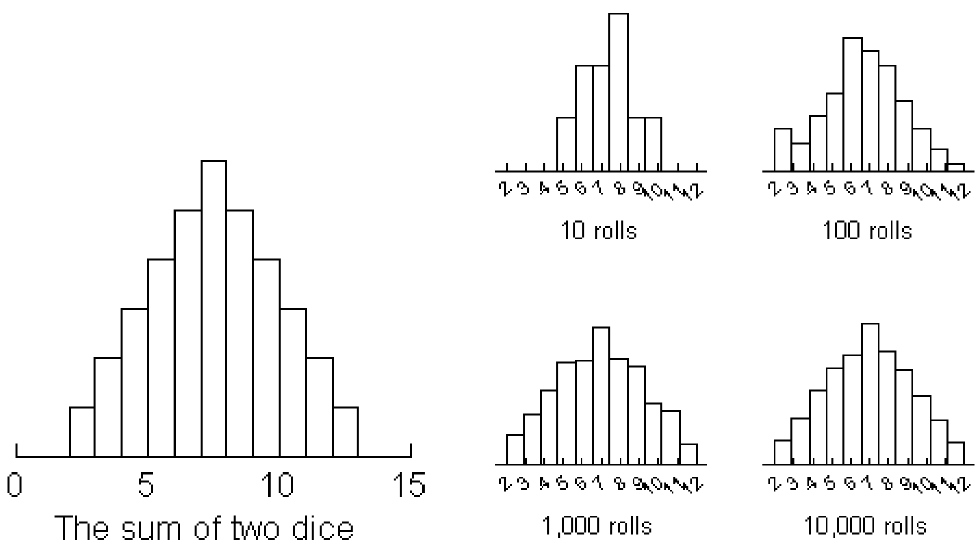
The standard deviation is not usually the uncertainty in the mean. Obviously the more measurements that are made the more precisely the average can be found. The error in the average (or error in the mean) is $\sigma_{\overline{x}}$:

$$\sigma_{\overline{x}} = \frac{\sigma_{N-1}}{\sqrt{N}}.$$

where N is the number of measurements taken.

This can be most easily seen if you think about the sum of a pair of dice. The sum can range from 2 to 12 but the most likely number is 7, because there are the most number of ways to add up to 7. The theoretical distribution is shown in Figure 2(a). The curve can be approximated by a Gaussian function (or bell curve). The higher the number of dice rolls, the closer the observed distribution will match the Gaussian distribution, assuming that the dice rolls are *randomly distributed about a mean.* In Figure 2(b) results are plotted for 10, 100, 1000, and 10,000 dice rolls, showing that as N gets larger, the histogram converges to a Gaussian, with a well-defined mean and standard deviation.

Remember, whenever you measure the mean of a sample, you should always calculate the associated σ_s and $\sigma_{\bar{x}}$.



(a) Theoretical (b) Observed

Figure 0.2: Distributions of numbers from two dice.

HOW TO REPORT YOUR ERRORS

You should always present your errors in two ways, if possible:

1. **Qualitative Errors:**
   You should always discuss your errors in a general way. A discussion of the errors should always appear in your Conclusion and/or Discussion sections. Especially try to consider errors and assumptions that were not discussed in the lab. Even if you cannot quantify these errors, you should discuss them.

2. **Quantitative Errors:**
   If you can estimate, calculate, or measure on error, you should always do it. You should also always fully propagate an error through calculations unless told otherwise.

COMPARISONS WITH ACCEPTED/THEORETICAL VALUES

In labs you will often be asked to compare your answer to an "accepted" or "theoretical" value (e.g. one that has been measured much more precisely with better or more data/techniques). When doing this comparison, you should *always consider your errors.*

Example: Suppose you calculate the distance to a star to be $d = 460 \pm 40$ pc, and you are asked to compare to the "accepted" value of $d = 482 \pm 2$ pc. Clearly, $460 \neq 482$. However, your answer is *not* 460 pc, it is 460 ± 40 pc. Thus, you are asserting that the true value lies in range from 420 to 500 pc. The accepted value, 482 ± 2 pc, does lie in that range, and thus your answer does agree with the accepted value.

Even an accepted value of $d = 501 \pm 2$ pc would still be in agreement with your answer, since the accepted value's uncertainty places it within your 1σ range.

To perform this comparison rigorously, use the following formula. If we are comparing two quantities, $a \pm \sigma_a$ and $b \pm \sigma_b$, they are consistent if:

$$|a - b| \leq \sigma_a + \sigma_b.$$

If your results are inconsistent with the accepted/theoretical value, check your systematic errors. Are there additional sources of uncertainty your neglected to mention or quantify?

Contents

1 THE DISTANCE OF THE HYADES STAR CLUSTER

"We find the universe terrifying because of its vast meaningless distances, terrifying because of its inconceivably long vistas of time which dwarf human history to the twinkling of an eye, terrifying because of our extreme loneliness, and because of the material insignificance of our home in space - a millionth part of a grain of sand out of all the sea-sand in the world. But above all else, we find the universe terrifying because it appears to be indifferent to life like our own..."

—Sir James Jeans, *The Mysterious Universe*, 1930

OBJECTIVE

The moving cluster method is applied to determine the distance to the Hyades open star cluster.

INTRODUCTION

A difficult task in astronomy is to determine the distances to various astronomical targets. For nearby objects, simple geometric methods can be used to find fairly accurate distances.

Annual Parallax

The first efforts by the Greeks to measure stellar distances were largely frustrated by inaccurate instruments and a lack of photographic plates. Aristotle reasoned that if the earth revolved about the sun, then the relative locations of the stars should be seen to shift, since an observer on earth would view the stellar arrangement from different positions (see Figure 1.1). Although Aristotle was not able to detect any such displacement, known as *annual parallax*, the method is sound, and is used today to measure the distances to stars within about 100 pc of the sun.

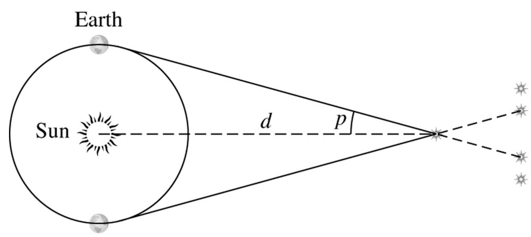


Figure 1.1: The geometry of the annual parallax method, from Carroll & Ostlie (2006). A star at distance d is observed to have a parallax of p.

EXAMPLE: Consider the following example from Carroll & Ostlie (2006). In 1838 Bessel published a parallax for the star 61 Cygni based on 4 years of observation. His value, $p = 0.316''$, corresponds to a distance of:

$$d \;=\; \frac{1}{p('')}\;\text{pc} \;=\; \frac{1}{0.316''}\;\text{pc} \;=\; 3.16\;\text{pc}.$$

(Note: You could then determine the uncertainty in this distance using the uncertainty in the measured parallax.)

For more distant stars the angles involved become too small to measure, and other methods must be used.

Stellar Motion

Of course, the stars have motions of their own, and do not remain fixed in the sky. That these stars do move perceptibly was first noticed in 1718 by Edmund Halley. He found the positions of Aldebaran, Sirius, and Arcturus to be half a degree different from those cataloged by Ptolemy, Hipparchus and Timocharis. He reasoned:

> "It is scarcely credible that the Ancients could be deceived in so plain a matter, three Observers confirming each other. Again their stars being the most conspicuous in Heaven, are in all probability the nearest to the Earth; and if they have any particular motion of their own, it is most likely to be perceived in them."

Modern observations have shown that Halley was correct: the stars do have their own intrinsic *space velocities*.

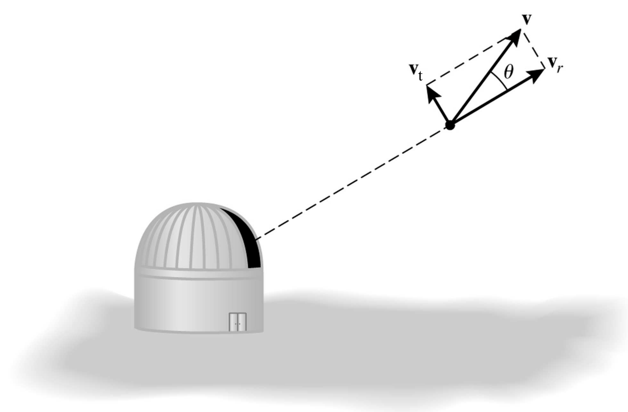


Figure 1.2: Motions of a star, from Carroll & Ostlie (2006). The space velocity, $\vec{v}$, can be broken up into its two components, the radial velocity ($\vec{v}_r$) and the transverse velocity ($\vec{v}_t$).

The space velocity (which is a vector with a magnitude and direction) can be broken up into its two components (see Figure 1.2):

1. A *radial velocity* toward or away from the Earth (v_r), and
2. A *tranverse velocity* perpendicular to the line of sight (v_t).

In order to know the true space velocity of a star, it is necessary to know *both* components.

Radial Velocity Stellar radial velocities can be measured directly from stellar spectra. Spectral lines from a moving body are Doppler shifted from their rest frame wavelengths as a result of the target's radial motion; the magnitude of the shift depends on the target's radial velocity. Thus, we have a relatively simple and reliable method of determining radial velocities; we need only measure the displacement $\Delta\lambda$ of a spectral line from its expected wavelength λ, provided the latter is known. The radial velocity, v_r, is then given by

$$\frac{v_r}{c} = \frac{\Delta\lambda}{\lambda}$$

where c is the velocity of light.

Transverse Velocity Transverse velocities cannot be directly measured, though a star's movement across the sky (its *proper motion*, often given in arcseconds per year) can be measured. Proper motions are generally measured by taking two pictures of a stellar field a few years apart. The change in position and direction of motion of a given star can be determined by measuring the change in its position between the two images, with respect to the background stars. Since the size of a stellar image on a picture is usually a sizable fraction of an arcsecond, the position of a star can be measured to an accuracy of only a few hundredths of an arcsecond. Therefore, in order to detect a proper motion of $0.1''$ per year it is necessary to allow an interval of several years to elapse between successive pictures.

The transverse velocity can only be calculated if the distance to the star is known. This can be understood using simple geometry (see Figure 1.3). Suppose an object at an unknown distance, d, is moving with a transverse velocity v_t. At time t_A the observer notes the object to be at point A. A short time Δt later, the object is observed at point B. The observer notes that in the interval of time Δt, the object has moved through a small angle, $\Delta\theta$. During time Δt, the object has covered distance x, which can be expressed in two ways:

$$\begin{aligned} x &= v_t \, \Delta t \\ &= d \, \tan \Delta\theta. \end{aligned}$$

The small-angle approximation for $\tan \Delta\theta$ can be used if $\Delta\theta$ is in radians. Since $\Delta\theta$ is typically measured in arcseconds, we must include a factor of 206265 to convert between radians and arcseconds. Then x can be rewritten as:

$$x = \frac{d \, \Delta\theta \, ('')}{206265}.$$

Combining the equations for x, solving for v_t, and assuming that we wish to know v_t in km/s, we find

$$v_t \text{ (km/s)} = \frac{d \text{ (km) } \Delta\theta \, ('')}{206265 \, \Delta t \text{ (s)}}. \qquad (1.1)$$

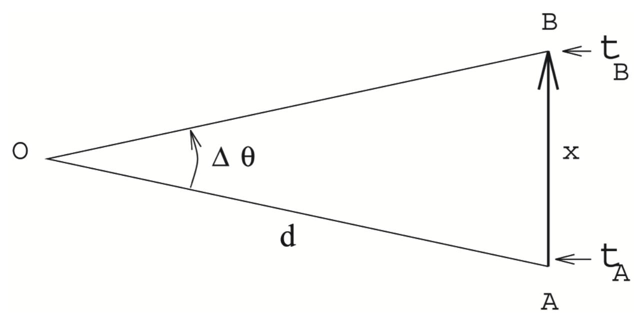


Figure 1.3: Transverse motion of a star.

The proper motion describes the angular distance covered in a certain time, and can therefore be written as

$$\mu \text{ ($''$/year)} = \frac{\Delta\theta \text{ ($''$)}}{\Delta t \text{ (year)}}.$$

Astronomical distances are often measured in pc rather than km. To use Equation (1.1), we must therefore convert the observed values (μ in $''$/year, d in pc) to the units in the Equation ($''$/s and km):

$$v_t \text{ (km/s)} = \frac{d \text{ (pc)}(3.09 \times 10^{13} \text{ km/pc}) \;\; \mu \text{ ($''$/year)}(0.316 \times 10^{-7} \text{ year/s})}{206265}.$$

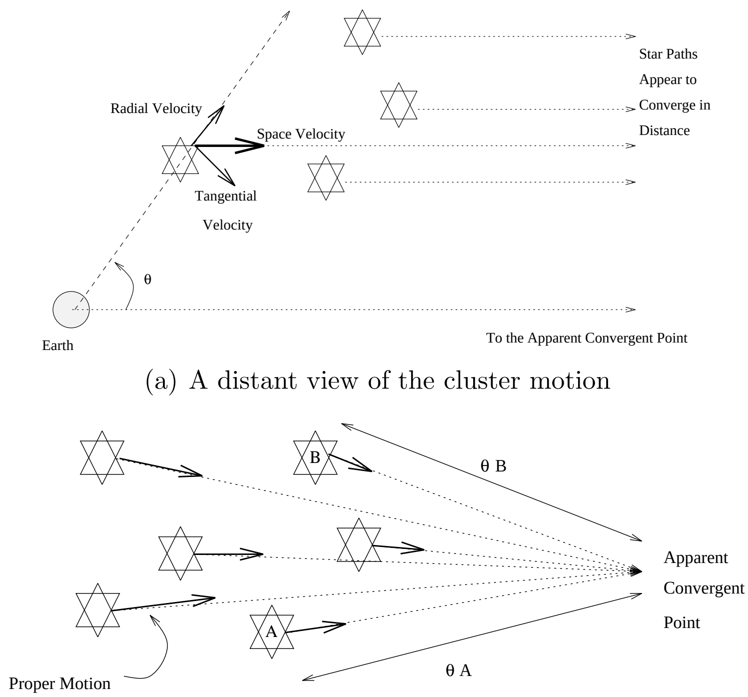
Thus, we obtain the final equation for v_t:

$$v_t \text{ (km/s)} = 4.74 \;\; d \text{ (pc)} \;\; \mu \text{ ($''$/year)}. \tag{1.2}$$

Again, normally this equation will be useful only if the distance is already known, since a star's v_t is not directly measurable.

Moving Cluster Parallax

Nearby star clusters provide a unique exception to the above rule of thumb since the space velocities can be found *without first knowing the distance.* This is possible because accurate proper motions are measurable for these nearby stars, which are all located at approximately the same distance.



(a) A distant view of the cluster motion

(b) Star motions as seen from Earth

Figure 1.4: Moving cluster.

If a group of stars moves exactly together, the stars should have parallel space velocity vectors as the cluster moves through space. Just as two parallel railroad tracks appear to converge in the distance, so also will parallel star paths. This point of convergence is determined on a chart of the sky by simply extending the lines of proper motion of each star, and finding their point of intersection (Figure 1.4).

The angle of sight between a star and the convergent point, θ, is equal to the angle between the true space velocity of a star, $\vec{v}$, and its radial velocity, v_r. The convergent point shows the direction of the space velocity; therefore, the angle between the star's position and the convergent point is also equal to θ (see Figure 4(a)). The radial velocity, v_r, can be measured from the stellar spectra. It is then a simple matter to solve the velocity right triangle for the transverse velocity component:

$$v_t = v_r \tan\theta.$$

With the transverse velocity v_t and the measured proper motion, we can then calculate the distance d to the star:

$$d\ (\mathrm{pc}) = \frac{v_r\ (\mathrm{km/sec})\ \tan\theta}{4.74\mu\ (''/\mathrm{yr})}. \tag{1.3}$$

As a reminder, this is only possible because the parallel space velocity vectors appear to converge, showing the direction of the space velocity vector (which allows us to solve for the transverse velocity). If this procedure is carried out for many stars in a nearby cluster, an average of the distances calculated will be a good indication of the actual distance to the cluster.

EQUIPMENT

A plot of the positions of some members of the Hyades star cluster is provided. A vector extends from each star, indicating the magnitude and direction of its proper motion. This data is obtained from measurement of the positions of the stars on pictures taken many years apart.

PROCEDURE

Step 1: Find the Convergent Point

With a ruler, carefully extend the vectors about 10 inches in the direction of the arrows. Because this cluster of stars is traveling through space as a unit, the lines will seem to converge (although they will not converge exactly).

Q: Decide the point of convergence, i.e. where the density of lines is greatest, and measure the coordinates of that point. What are the Right Ascension and Declination of the convergent point? What is the uncertainty in this position?

Step 2: Measure Angles

Ten stars are identified on the handout. For each star the angle, θ, between the star and the convergent point (shown in Figure 4(a) must be measured on the handout. This angle will actually be measured as a *distance* on the sky. You will have to use the declination scale on the right side of handout to find the scale of the diagram in degrees; you can then convert the distance to an angle.

Q: What are the values of θ for each star? Present the results in a table, leaving two columns for stellar distance.

Step 3: Compute Distances using Moving Cluster Parallax

Table 1.1 lists the radial velocities and proper motions for 10 stars in the cluster. Use these values, your measurements of θ, and Equation (1.3) to compute the distance to each of the 10 stars.

Q: What are your distances to each star? Record the values in your table.

Step 4: Estimate Uncertainties

For at least one of the stars estimate the uncertainty in the distance due to the uncertainty in the radial velocity, the uncertainty in the proper motion, and your inability to precisely determine the convergent point. If you are using a program for your computations, estimate the uncertainty for all of them.

Q: Record these uncertainties in your table. Which of these uncertainties causes the largest uncertainty in the distance? Which of these uncertainties will affect the distances in a random manner? Which will be a systematic error?

Step 5: Find the Average Distance

Average these distances, calculate the standard deviation, and find the uncertainty in the mean. Remember, this standard deviation includes both the random errors *and* the intrinsic spread in the distances.

Q: How many of your distances are included with one standard deviation of your mean? Does this agree with what you would expect for a random distribution? (See the Errors section at the front of the lab manual for a review of random errors.)

ADDITIONAL QUESTIONS

1. What is the mean distance in light years to the Hyades? Compare to the value given by the HIPPARCOS satellite of 151 ± 1 light years.
2. What assumptions have you made concerning the method in general? (In particular, consider several reasons why the distances to the individual stars differ from each other.) Are these uncertainties quantified in your errors?
3. The cluster of stars has an extent up-down, left-right, and front-back. What are these values (in pc or ly)? Is the cluster spherical?
4. Will the cluster ever reach its convergent point? Why or why not?
5. The HIPPARCOS value was calculated using annual parallaxes. Which method do you think is more accurate? Why?

References

Carroll, B.W. & Ostlie, D.A. 2006, Benjamin Cummings (2nd ed.; New York)

Table 1.1: Proper motions and radial velocities of ten Hyades stars.

Star	Hipparcos ID	Proper Motion, μ (''/year) ± 0.0008	Radial Velocity (km/sec) ± 0.5
1	18170	0.1470	31.6
2	19504	0.1278	31.0
3	20215	0.1267	36.6
4	20455	0.1115	38.3
5	20567	0.1029	43.8
6	21543	0.0886	38.2
7	22044	0.0998	39.3
8	22550	0.0880	38.6
9	23497	0.0801	43.6
10	23983	0.0640	38.8

2 CHARACTERISTICS OF A CCD

OBJECTIVE

To investigate the precision of measurements made with a Charge Coupled Device (CCD).

INTRODUCTION

In order for astronomical observations to be scientifically rigorous, the observed data must be accurately recorded. Any device that is used to record astronomical observations must meet several criteria:

1. Since astronomical objects are often quite faint, the detector must be efficient at capturing the incident light.
2. The detector must not add extra signals or significant noise to the images, so that measurements of the data will be reasonably accurate and precise (i.e. the detector should not introduce strong random or systematic errors).
3. The detectors and data must be easy to work with.

The most popular recording devices throughout most of the twentieth century were photographic plates, i.e. pieces of glass that were covered with a light-sensitive coating. These plates worked well for much of the twentieth century, yet were not practical for the digital age, since digitizing photographic plates requirings scanning the images and converting them to digital formats. Furthermore, photographic plates are not suitable for distant, faint targets, as they are fairly inefficient at collecting light—according to Janesick & Blouke (1987), the photon collecting efficiency of a typical plate is only about 1%, meaning that for every 100 photons that strike the plate, only 1 will be recorded. Photographic plates also have a nonlinear response to light, so that increasing the integration time does not necessarily increase the signal-to-noise ratio, or S/N, by a significant amount (Wagner, 1992). Finally, the design and set-up for photographic plate observations are rather fragile, making it difficult to set up observations or move observatories into space. Ultimately, photographic plate technology, while successful in the past, was limited in its ability to perform astronomical observations.

The Charge-Coupled Device, or CCD, was created in 1969. Its introduction to astronomy revolutionized the field, allowing observations of fainter targets than with photographic plates, and with less noise and more precision.[1] The general concept of the CCD is fairly simple: the design of the CCD is based on the final image it creates. A greyscale image is nothing more than a collection of pixels arranged in a grid. Each pixel is assigned a number, which represents the intensity (or brightness) of that pixel. As a detector, the CCD is simply an array of pixels, each of which captures the incident photons in order to determine the brightness at each point on the sky.

The CCD uses electrons (or charge) as its basic unit of information, and therefore a CCD must perform the following tasks:

1. **It must generate electrons for each photon that hits the detector.** The CCD pixels are made of special material, so that when photons strike the atoms in the CCD, they *ionize* electrons from the atoms. Thus, each photon will produce an electron, meaning that the CCD response should be linear (i.e. doubling the exposure time should double the number of incident photons, which should double the number of electrons).

2. **It must collect the electrons and store them while more are accumulating.** Thus, the CCD must be able to contain the electrons and prevent them from leaking into nearby pixels.

3. **It must transfer the electrons off the CCD to a device that can interpret the information.** This is done by shifting the charge from pixel to pixel until it is shifted onto the detector.

4. **It must amplify and count the electrons, and convert this number into a digital intensity.** This is accomplished with an analog to digital converter; the units of intensity that we measure are therefore Analog to Digital Units, or ADUs. The relationship between ADUs and electrons depends on the *gain* of the detector, i.e.

$$\text{gain} = g = \frac{\#\text{ of electrons/pixel}}{\#\text{ of counts/pixel}} = \frac{N_e}{N_{\text{ADU}}}. \tag{2.1}$$

[1] Because of its outstanding contributions to science, the inventors of the CCD, Willard S. Boyle and George E. Smith of Bell Laboratories, were each awarded a quarter of the 2009 Nobel Prize in Physics.

Of course, a CCD is not a perfectly efficient device. As with any measurement, there is an inherent uncertainty just from counting the incoming photons. The detector also does not detect all of the incident light; the ability of the CCD to detect incoming photons is quantified by its *quantum efficiency*. Furthermore, the CCD can create extra charge and/or lose charge during observations. We consider a few of the main sources of noise below.

Poisson noise: The photons from a distant source arrive at the detector randomly, meaning that even for pixels that should be the same brightness, the numbers of incident photons will differ slightly. The function describing the probability of the arrival of the photons is a discrete distribution known as the *Poisson distribution*. This Poisson noise is *not* introduced by the detector. *Even a perfect detector would record images with Poisson noise.*

If there are no other sources of error then the noise per pixel is defined by the Poisson distribution:

$$\text{noise} = \sigma_e = \sqrt{count} = \sqrt{N_e} \tag{2.2}$$

and the signal-to-noise ratio, S/N, would be:

$$\text{S/N} = \frac{N_e}{\sqrt{N_e}} = \sqrt{N_e}. \tag{2.3}$$

If the rate at which photons hit the detector per second, S, is constant, then the number of electrons generated in a certain exposure time t is $N_e = St$.

Cosmic rays: When cosmic rays hit the CCD, they leave bright spots that can affect the image. The effects of cosmic rays can be reduced by taking multiple images and averaging them together.

Bias: The pixels do not all have the same zero points—some may intrinsically appear brighter or fainter than others. This difference in zero point values is known as *bias*, and can be removed by taking a *bias frame*, i.e. a zero second image without any incident light.

Pixel-to-pixel variations: The pixels in a CCD operate as individual units. Each pixel may have a slightly different efficiency at collecting the incident photons or storing the resulting charge. Thus, a CCD will have pixel-to-pixel variations. To identify and remove these variations, the CCD is uniformly illuminated, which shows which pixels appear brighter or fainter than others. These *flat field* images are usually taken by illuminating and observing the inside of the dome.

Dark current: It is possible for the electrons to be thermally ionized even when no photons are present. This extra charge is known as *dark current*. It can be minimized by cooling the CCD, and it can be removed by taking long exposures with no light on the CCD (known as *darks*). With the addition of dark current, D, the noise becomes

$$\sigma_e = \sqrt{St + Dt}.$$

Read noise: This error is introduced when the charge is amplified, counted, and transformed into ADUs (Step 4 above); this error can usually be estimated fairly accurately.

With the read noise, R, we obtain the final *theoretical noise equation*:

$$\sigma_e = \sqrt{St + Dt + R^2} \tag{2.4}$$

which leads to a S/N of:

$$\mathrm{S/N} = \frac{St}{\sqrt{St + Dt + R^2}}. \tag{2.5}$$

To summarize, some of these sources of noise can be removed through calibration observations, i.e. with the *biases*, *darks*, and *flats*. The read noise can be estimated, while cosmic rays and Poisson noise can be reduced with multiple observations of the same target. Our goal is to understand these sources of error, in order to minimize or remove them as much as possible.

EQUIPMENT

For this lab we will use the CCD camera system STAR I on the Climenhaga 0.5 meter telescope in the Elliott building. The STAR I camera contains a CCD chip called a Thompson CCF TH7883CDA, which has 576 by 384 pixels, each 23 microns square. This system has a 12-bit analog to digital converter (ADC), which means that the largest intensity number possible, in AD units (ADUs), is $2^{12} = 4096$. Any counts over this number will *saturate* those pixels. The number of electrons per ADU depends on the gain setting of the on-chip amplifier, either gain 4 or gain 1. For this chip, at gain 4, the read noise is equal to 15 electrons. The quantum efficiency of the CCD is around 40%. The STAR I system minimizes dark current by thermally cooling the CCD chip to about -50^o Celsius. The colder the chip the lower the dark current, so many observatories use liquid nitrogen to achieve even lower temperatures (-196^o C).

For the data analysis we will be using the Image Reduction and Analysis Facility (IRAF). See Appendix B for a brief description of how to preform basic commands in IRAF.

PROCEDURE: PART 1

The telescope uses a rather old computer system, and can be tricky to use. Many of the commands are performed using the number keys at the top of the keyboard, which should be labelled. The monitor on the right shows the images that were just observed. Clicking on a pixel in the image shows the intensity of that pixel, in ADUs.

To save the images to disk, hit the "Dump to Disk" button. This will save the image to the computer. **Be sure to write down the names of each image.** The name will be a number.

Step 0: Prep the telescope

Ensure that the telescope covers are off. Check that the computers and monitors are on. Ensure that the gain is set to 4 (check the monitor on the right).

Step 1: Take a bias frame

Change the filters to "DC" and take a 0.0 second exposure.

Step 2: Take a dark frame

Take a 100-second exposure with the same "DC" filters.

Q: Do you see any tiny one- or two- pixel bright spots? These are cosmic ray hits on the CCD chip. How many cosmic ray hits can you see? How many hits per second?

Step 3: Take dome flats

Set the filters to **CC**, illuminate the dome with the lamp, and take a 0.1 second exposure. Take another frame with twice this exposure time. Repeat taking frames with twice the previous exposure time until you finish with an exposure time of 51.2 seconds.

Ensure that you have recorded the file names of your observations!

PROCEDURE: PART 2

Step 0: Prep files

Your TA has moved the files off the dome computer and converted them to a workable format. Locate your files, and ensure that they are in the correct format (i.e. that they have .fits extensions). Download and/or move them to the correct directory. Also download or move Bias.fits and Flat.fits to the correct directory. If your computer is named lab37, then you move the files to `/lab37_1/scratch/a200`. Your files will all have numerical names, e.g. 24520o.fits.

Step 1: Process the images

To analyze your images, you will first need to remove the bias and flat fields from them. To do this, start IRAF (see Appendix B) and load the imred and ccdred packages. Then edit the parameters of the task *ccdproc* to tell it how to process your images (as shown below). If your images are named, e.g., 24520o.fits, 24521o.fits, etc., then you can select all of them using the asterisk wildcard (e.g. `245*o.fits`). If you wish, you can use your own bias instead of the master one.

```
                                  I R A F
                    Image Reduction and Analysis Facility
PACKAGE = ccdred
   TASK = ccdproc

images  =            2*o.fits  List of CCD images to correct          *
(ccdtype=              object) CCD image type to correct              *
(max_cac=                   0) Maximum image caching memory (in Mbytes)
(noproc =                  no) List processing steps only?

(fixpix =                  no) Fix bad CCD lines and columns?
(oversca=                 yes) Apply overscan strip correction?      *
(trim   =                 yes) Trim the image?                       *
(zerocor=                 yes) Apply zero level correction?          *
(darkcor=                  no) Apply dark count correction?          *
(flatcor=                 yes) Apply flat field correction?          *
(illumco=                  no) Apply illumination correction?
(fringec=                  no) Apply fringe correction?
(readcor=                  no) Convert zero level image to readout
correction?
(scancor=                  no) Convert flat field image to scan correction?

(readaxi=                line) Read out axis (column|line)
(fixfile=                    ) File describing the bad lines and columns
(biassec=         [1:2,1:576]) Overscan strip image section          *
(trimsec=       [6:384,1:576]) Trim data section                     *
(zero   =           Bias.fits) Zero level calibration image          *
(dark   =                    ) Dark count calibration image
(flat   =           Flat.fits) Flat field images                     *
(illum  =                    ) Illumination correction images
(fringe =                    ) Fringe correction images
(minrepl=                  1.) Minimum flat field value
(scantyp=           shortscan) Scan type (shortscan|longscan)
(nscan  =                   1) Number of short scan lines

(interac=                  no) Fit overscan interactively?
(functio=            legendre) Fitting function
(order  =                   1) Number of polynomial terms or spline pieces
(sample =                   *) Sample points to fit
(naverag=                   1) Number of sample points to combine
```

```
(niterat=                    1) Number of rejection iterations
(mode   =                  ql)
```

Execute this task. Note that *ccdproc* will replace your old images with the processed ones.

Step 2: Find the mean and standard deviation of counts in the images

The IRAF task *imstat* will find the mean and standard deviation of the counts in a specified region of the image. We will use a 20×20 pixel^2 region for these statistics. To execute this task, simply type:

cc >**imstat 245*o.imh[100:120,100:120]**

The printed output will show the mean and standard deviation of that 20×20 pixel^2 region, in ADUs. Be sure that you are looking at the correct values, as the columns do not always line up.

Q: Record these values in Table 2.1. Do these values agree with what you would expect for a Poissonian distribution?

Step 3: Test the linearity of the CCD

As discussed in the lab introduction, the CCD's recorded intensity (i.e. the signal) should be *linear* with time, because increasing the exposure time enables more photons to hit the detector, which will create more electrons. To test this assumption we can make a plot of the number of counts versus exposure time. In the terminal, open a new file called `linear` (using, e.g., gedit; see Appendix A) and enter the numbers into the file in the following format, which each exposure on a different line:

$$x_1 \;\; y_1$$

$$x_2 \;\; y_2$$

etc.

We can then use IRAF's *graph* task to plot the data:

```
                              I R A F
                  Image Reduction and Analysis Facility

*       input = "linear"       list of images or list files to be graphed
         (wx1 = 0.)            left  world x-coord if not autoscaling
         (wx2 = 0.)            right world x-coord if not autoscaling
         (wy1 = 0.)            lower world y-coord if not autoscaling
         (wy2 = 0.)            upper world y-coord if not autoscaling
         (wcs = "logical")     Coordinate system for images
        (axis = 1)             axis along which projection is to be taken
   (transpose = no)            transpose the x and y axes of the plot
*  (pointmode = yes)           plot points instead of lines?
      (marker = "box")         point marker character?
    (szmarker = 0.005)         marker size (0 for list input)
      (ltypes = "")            List of line types (1-4)
      (colors = "")            List of colors (1-9)
*       (logx = yes)           log scale x-axis
*       (logy = yes)           log scale y-axis
         (box = yes)           draw box around periphery of window
  (ticklabels = yes)           label tick marks
*     (xlabel = "Time")        x-axis label
*     (ylabel = "Signal ")     y-axis label
     (xformat = "")            x-axis coordinate format
     (yformat = "")            y-axis coordinate format
*      (title = "Linearity")   title for plot
     (lintran = no)            perform linear transformation of x axis
          (p1 = 0.)            start input pixel value for lintran
          (p2 = 0.)            end input pixel value for lintran
          (q1 = 0.)            start output pixel value for lintran
          (q2 = 1.)            end output pixel value for lintran
         (vx1 = 0.)            left limit of device viewport (0.0:1.0)
         (vx2 = 0.)            right limit of device viewport (0.0:1.0)
         (vy1 = 0.)            bottom limit of device viewport (0.0:1.0)
         (vy2 = 0.)            upper limit of device viewport (0.0:1.0)
       (majrx = 5)             number of major divisions along x grid
       (minrx = 5)             number of minor divisions along x grid
       (majry = 5)             number of major divisions along y grid
       (minry = 5)             number of minor divisions along y grid
    (overplot = no)            overplot on existing plot?
      (append = no)            append to existing plot?
      (device = "stdgraph")    output device
*      (round = yes)           round axes to nice values?
        (fill = yes)           fill viewport vs enforce unity aspect ratio?
        (mode = "ql")
```

Note that this will generate a log-log plot.

After you have executed the task the graph will appear in a separate window. Type

cc > `=gcur`

into the terminal to flush the graphics buffer. Then type `=` to send a hard copy to the print. Hit `q` to exit the window.

Q: Is the graph linear? Where and why does this linearity break down? What is the slope of this line? What does the slope tell you?

Step 4: Examine the noise

We now want to examine how the noise changes with the number of counts. Enter your mean and standard deviation values (in ADUs) into a file called `sigerrADU`. Then use the following awk script to convert from ADUs to electrons:

cc >`!awk '{print $1 *` *gain*`, $2 *` *gain*`}' sigerrADU > sigerr`

Of course, you'll use the appropriate gain value in the above line, instead of the word "gain."

Q: What value did you use for the gain? What are your values for N_e and σ_e? Record them in Table 2.1.

Next, use the IRAF task *graph* to plot the log of the signal ($\log N_e$) against the log of the error ($\log \sigma_e$), which are now in the file `sigerr`. Remember that there is a setting in *graph* to automatically make the log-log plot, so you do not need to calculate the log values. Be sure to change the axis labels and title.

Q: What is this plot showing, qualitatively? (I.e. how does the noise change with increased signal, or, equivalently, exposure time?) Assuming that the dark current is negligible, use this graph and Equation (2.4) to estimate the read noise. Explain your reasoning.

Step 5: Examine the relative noise (i.e. the S/N)

We will now investigate how the relative error changes with the signal (or, equivalently, exposure time). To do this, we will plot $\log(N/S)$ against the log of the signal, $\log N_e$. Calculate the N/S value with the following awk script:

```
cc >!awk '{print $1, $2/$1}' sigerr > relerr
```

Then use the *graph* task to make the plot.

Q: Qualitatively, what is this plot showing? Record your N/S values in Table 2.1. How many photons would need to hit the detector in order to get a $S/N = 100$? Explain.

Step 6: Calculate the theoretical noise

Use Equation (2.4), assuming negligible dark current, to find the theoretical noise values.

Q: Record your theoretical noise values in Table 2.1. How do they compare to the measured values? Is there a trend with exposure time? What does this discrepancy imply? Do you think including dark current would make a difference?

Step 7: Verify the gain of the detector

The definition of gain tells us that:

$$\begin{aligned} N_e &= gN_{\mathrm{ADU}}, \quad \text{and} \\ \sigma_e &= g\sigma_{\mathrm{ADU}}. \end{aligned}$$

Assuming a perfect detector, Poissonian statistics are the sole source of noise, and

$$\sigma_e = sqrtN_e.$$

It is then clear that we can relate the gain to the observed counts and standard deviation, in ADUs:

$$N_{\mathrm{ADU}} = g\sigma^2_{\mathrm{ADU}}.$$

Q: Is this a Poissonian distribution? Discuss.

This relation shows that the gain can be found by graphing N_{ADU} against σ^2_{ADU}. Make this graph in IRAF. Note that the graph can be separated into two regions. Use the longer exposure, linear part to find the gain.

Q: What value do you calculate for the gain? Does this agree with what you expect? Discuss.

ADDITIONAL QUESTIONS

We now have all the knowledge we need to determine the exposure time needed to obtain to observe the 12th magnitude quasar, 3C273. distant with our CCD.

1. We want to obtain $S/N = 100$ in our observations. How many electrons do we need to collect for this S/N?

2. We know that a zero-magnitude star such as Vega gives approximately 1000 photons $\cdot$ s^{-1} $\cdot$ cm^{-2} $\cdot$ Å^{-1} at the top of the atmosphere. Our primary mirror is 0.5 meter in diameter, the secondary mirror is about 0.25 meters in diameter, and each reflects about 80%. With no filter, our band pass is about 2000 Å. The CCD's quantum efficiency is about 40%. There is also a window on the dewar above the CCD and 5% of the light is reflected at each glass-air interface. How many photons would our CCD detect from Vega in one second?

3. Recall the definition of magnitude: $m_1 - m_2 = -2.5 \log(f_1/f_2)$, where f is the stellar flux. What is the exposure time needed to obtain $S/N = 100$ for 3C273?

References

Janesick, J. & Blouke, M. 1987, *Sky and Telescope*, 9, 238

Wagner, R.M. 1992, *ASP Conf. Series*, 23, 160

Table 2.1: Data summary.

	Frame	t (sec)	N_{ADU}	σ_{ADU}	N_e	σ_e	σ_e/N_e	Noise
1	bias	0		n/a	n/a	n/a	n/a	n/a
2	dark	100						
3	data							
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

3 VISUAL OBSERVATIONS

The objective of this laboratory exercise is to introduce the student to the essentials of astronomy - the stars, nebulae, and telescopes. People have looked at the sky with their unaided eye for centuries and have made some interesting observations. The most obvious is that everything in the sky other than the sun and the moon seems to be a tiny pin prick of light. If you measure the moon's position relative to some stars tonight and then do the same thing tomorrow you will find that the moon has moved relative to the stars. The ancients also noticed that some of the brightest "stars" moved; these they called the "planets", which means "wanderers". If possible your instructor will point out some planets. You will probably notice that the stars seem to form lines or groups. Instead of always saying the bright star with two dim ones beside it, the ancient Arabs named the stars and the Greeks named the groups or constellations of stars. Your instructor will point out the more obvious constellations and bright stars.

What you look at with your telescope will depend on the season, the moon, the planets and mostly the weather; however, some general guidelines can be given. Always look at the brightest, most easily found objects first.

The planets are also bright and usually easily identified. What color are they? Can you see markings on their surfaces? Can you see their moons? Are they crescent-shaped, round, or gibbous?

Even if the moon and the planets are below the horizon during the night, there are many very interesting stars to look at. Point your telescope to any star in the sky; and what do you see? Hopefully you will see a tiny pin prick of light that twinkles. Stars look the same through a telescope as they do to your eye, but brighter. They seem so small because they are much farther away than the planets. Some stars have close companions which orbit them, similar to the way our earth orbits the sun. An example of one of these binary star systems is the second star going up the handle of the Big Dipper. This star is called Mizar and has a dim companion beside it, called Alcor, which you may be able to see with your naked eye. If you look at Mizar with your telescope you can see that it is a close double. From Norton's Star Atlas we find that these two stars are about 15 seconds of arc apart. Estimate how large the stars appear to be. This apparent size of a star is called the seeing disc of a star. If the atmosphere is very turbulent the seeing is poor and the stars appear large.

Another observation to make is to tell whether a star is red or blue.

Table 3.1: INTERESTING FALL OBJECTS

Objects	R. A.	Dec	Mag	Comments
Vega	18:36:56	$+38^o47'$	0.0	25 ly A0V
Arcturus	14:15:40	$+19^o11'$	0.0	36 ly K2III
Albireo	19:30:44	$+27^o57$’	3.1	K3II+B8V
h&χ Per	2:20	$+57^o08'$	6.6	6000 ly Open Cluster
M11	18:51:06	$-6^o16'$	5.8	6000 ly Open Cluster
M27	19:59:24	$+22^o43'$	7.6	900 ly Dumbbell Nebula
M57	18:53:35	$+33^o01'$	8.8	2300 ly Ring Nebula
NGC 7662	23:25:54	$+42^o32'$	8.6	3000 ly Blue Snowball
M31	0:42:42	$+41^o16'$	3.5	2,000,000 ly Andromeda Galaxy
M13	16:41:42	$+36^o28'$	5.9	20,000 ly Globular Cluster
M15	21:30:00	$+12^o10'$	6.3	30,000 ly Globular Cluster

Albireo (β Cygni) is a double star composed of one red and one blue star.

Other objects you may wish to observe are clusters of stars, gaseous nebulae and galaxies. These objects are generally very distant and thus are quite dim, and therefore hard to find with a small telescope so we may observe them through the large telescope.

From these examples your instructor will choose objects for you to observe.

EQUIPMENT

The amount of light that you see during the night is limited by the size of your pupils. You see only that light that passes through the pupil of your eye, which is only about 1 cm in diameter. (If your pupils were two or three centimeters across you could see at least ten times fainter.) For this lab we will give you a telescope, which concentrates all the light which falls on a mirror 20 cm across into a beam small enough to fit in your eye. These telescopes also magnify about 45 times and have a field of view of 1.25 degrees.

Draw a diagram of a telescope showing the essential parts: primary mirror, secondary mirror, eyepiece, focuser, and mount. In a few sentences describe and explain the function of each of these parts. If you look at a star with this telescope how much more light will you see compared to your unaided eye?

Your instructor will show you the parts of the telescope, how to use it, and explain where to look. Make sure you understand the use of the instrument before you try to use it in the dark.

OBSERVATIONS

1. Make a rough sketch of the moon as seen with your eye and as seen through the telescope. Label the sketch N, S, E, and W to show that the telescope inverts the image. Plot the moon's position on your star map.

2. Observe any of the planets, and draw diagrams showing the position of any surface features, moons...

3. Observe the double star Albireo (β Cyg). The apparent separation of these two stars is 34 seconds or arc. Comment on the color and apparent size of these two stars.

4. Observe the double star Mizar. The apparent separation of these two stars is 15 seconds or arc. Comment on the color and apparent size of these two stars.

5. Sketch five constellations which you have learned tonight and describe where they are in the sky. Label five stars in these constellations with their names.

6. Find, sketch and describe an example of an Open Cluster, a Globular Cluster, a Nebula and a Galaxy. Can you resolve each of these objects into its stars? Why or why not?

7. Compare the number of stars visible at different galactic latitudes. Point your telescope to various different constellations and count the stars visible in the eyepiece. Be sure to include the Big Dipper and Cassiopeia. Why are there differences?

8. Find and describe the various coordinate systems in the sky - the equatorial, the ecliptic and the galactic systems.

9. We know that the Earth rotates through 360^o in 24 hours so to measure the field of view of a telescope, we can turn off the telescope's drive and time how long it takes for a star to drift through the field of view. Your instructor will help set this up.

4 GALAXIES, STARS AND NEBULAE

INTRODUCTION

The photographs that we will be using are reproductions of plates taken by the 1.2 m (48 in) Schmidt telescope on Mount Palomar. Schmidt telescopes are designed specifically for photographing relatively large (by astronomical standards) areas of the sky with very good definition. This particular Schmidt telescope is the largest one in the world and was designed, at least in part, with the idea of compiling an atlas of the entire sky visible from southern California. The atlas took about 10 years to complete, under the auspices of the National Geographic Society, and the Hale Observatories which are run by the Carnegie Institution and California Institute of Technology. It has since been invaluable to astronomers. The telescope was large enough that the pictures include the most distant objects known, and yet the field of view was wide enough (In a large telescope the field of view is usually quite small) that the entire sky is covered by a reasonable number of photographs. Astronomers use the photographs both for survey work in determining the numbers and kinds of different classes of astronomical objects and for discovering and identifying objects that need to be studied further with other types of telescopes.

The original photographs were made on glass, as are most astronomical photographs, because glass is less subject to the stretching, shrinking and warping that can occur with the acetate and other bases used for ordinary photographic film. The original photographs are stored in a vault, but many copies have been made and sold to various observatories and astronomical institutions around the world. All the copies (ours are prints but transparencies are also available) are negative contact copies because, as a matter of practical experience, these preserve more of the details of the original than do any other types of copies. Each print is about 35 cm square and covers an area of the sky of 6^o x 6^o giving a scale of roughly one degree per 6 cm. (The full moon would thus be about 3 cm in diameter.) For each position on the sky, there are two different photographs, one taken originally in blue light and one taken in red light. This lets us estimate the colors of different objects and even, in extreme cases, see objects in one color that are nearly or totally invisible in the other.

These prints are of extremely high quality and are the same ones that astronomers use. They are very difficult to replace so please be extremely careful. Please NO PENS OR PENCILS ANYWHERE NEAR THE PHOTOGRAPHS! DO NOT WRITE ON PAPER THAT IS ON TOP OF THE PHOTOGRAPHS!

BASIC DATA

In the upper left hand corner of each photograph (which corresponds to the northeast corner on the sky) is a block containing the basic information about the photograph. This information includes the plate sensitivity (whether it was sensitive to blue light=O or to red light=E), plate number (the red and blue photographs of the same piece of sky will have the same number), the date on which the original photograph was taken, and the astronomical coordinates (right ascension and declination, which are analogous to latitude and longitude on the earth) which indicate the exact position in the sky of the center of the photograph.

OBJECT

1. To recognize the importance of practice in looking at photographs of astronomical objects.

2. To be able to recognize visually spiral and elliptical galaxies in both face-on and edge-on orientations.

3. To estimate the distance to one cluster of galaxies given the distance to another.

4. To appreciate the usefulness of photographs of more than one color.

5. To recognize the variety of objects visible in the sky.

GALAXIES

INTRODUCTION

The upper left corner of each print has a number which identifies the area of sky it covers. In this exercise you will be using prints 0-83 and 0-1563. Remember that these are negatives, so that light from a star or galaxy appears black on the prints. The spikes and circles around the images of bright stars are an artifact of the telescope structure. All stars, except of course the sun, appear as points of light to even the largest telescopes. The faint circular images which appear here and there are "ghost" images of stars which arise when light from a bright star bounces off the photograph, then gets reflected somewhere inside the telescope and finally returns somewhere else on the photograph.

PROCEDURE

1. Hercules Field

Inspect the print labeled 0-83 for a while. Most of the dots in the print are foreground stars in our Milky Way. This print also shows hundreds of galaxies which are not immediately apparent until you have achieved some experience with the other print.

2. Virgo Cluster

Now study the print 0-1563. You will notice many objects here that are clearly not stars. They are galaxies, mostly belonging to a cluster of galaxies in the constellation Virgo, called the Virgo Cluster of Galaxies. It is the nearest cluster of galaxies to us. We can say that these galaxies are all at approximately the same distance from us (about 51 million light years) and, therefore, any differences we find in the size or brightness between different galaxies are an indication of the intrinsic properties of these galaxies and not due to differences in their distance from us.

Study the print with a magnifier long enough to be able to distinguish:

a) elliptical galaxies (they show no structure, but get fainter from the center out) from spiral galaxies.

b) spiral arms of spiral galaxies that are smooth bands of light from those that are clumpy.

c) spiral galaxies seen edge-on from those seen face-on.

d) spiral galaxies which show a distinct bar across the nucleus (barred spirals).

e) irregular galaxies or peculiar systems like pairs of galaxies which might be colliding or orbiting each other. One of the best ways to look at galaxies carefully is to try to sketch some of them. Sketch at least 6 different galaxies (one from each of the above groups) in boxes about 3 cm square. Classify each galaxy as to which of the above groups it belongs.

3. Dust Lane

Near the upper right corner of 0-1563, just above the giant elliptical galaxy M86, is an elongated galaxy with a white lane across it NGC 4402. Sketch this system. What do you think the white lane is? Why are no stars visible where the white lane is?

Can you see white lanes or patches in any other galaxies? In what type of galaxy is there a tendency for white lanes and patches to occur?

4. Hercules Cluster

Now return to print 0-83. With your new experience, you will be able to find a group of several hundred galaxies clumped in a part of this print. Make a rough sketch of the features in the print showing location and outline of the cluster of galaxies (not the individual galaxies). This is the Hercules Cluster of Galaxies, in the constellation Hercules. Use a magnifier to check whether the Hercules Cluster contains spiral and elliptical galaxies like the Virgo Cluster. What do you find?

5. Distance to Hercules Cluster

Astronomers assume that the larger galaxies in each cluster are in fact very similar in size.

a) Why do the galaxies in the Hercules Cluster look so much smaller than those in the Virgo Cluster?

b) Estimate the distance of the Hercules Cluster, given that the Virgo Cluster is 51 million light years away. (Freedman et al., 1994). To do this, use your magnifier to measure the sizes of the approximately largest galaxies in each cluster, noting the type of galaxy beside each measurement (elliptical, E, or spiral, S). Then use the average size of the brightest galaxies as an indicator of relative distance.

Notes:

i) You will need to think carefully about the criterion you use for measuring size and then try to apply the same criterion to all your measurements.

ii) Estimate roughly the accuracy of your result.

iii) Compare the sizes you measured for the elliptical and spiral galaxies separately and discuss any differences you notice.

STARS AND NEBULAE

INTRODUCTION

The upper left corner of each print has a number which identifies the area of sky it covers. There is a red (E) print and a blue (O) print for each area.

Prints 1099 and 754 cover adjacent areas of sky and you can arrange them as shown in the diagram. The area covered is 6^o x 12^o, in the constellation Cygnus, where we are looking along a spiral arm of our galaxy. The very bright star Deneb is at the line of overlap as shown in the diagram and the direction of the Milky Way is marked.

The spikes and circles around the images of bright stars are an artifact of the telescope structure. All stars, except of course the sun, appear as points of light to even the largest telescopes. The faint circular images which appear here and there are "ghost" images of stars which arise when light from a bright star bounces off the photograph, then gets reflected somewhere inside the telescope and finally hits somewhere else on the photograph.

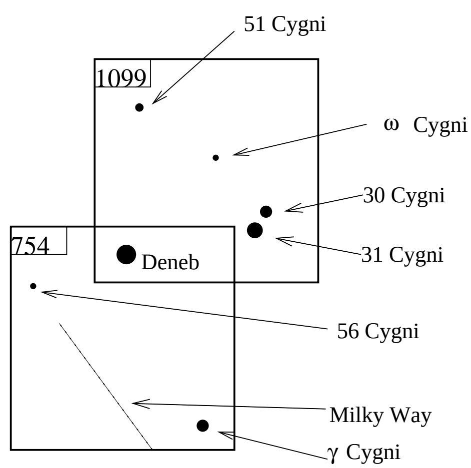


Figure 4.1: The Stars and Nebulae Prints.

PROCEDURE

Make a sketch similar to Figure 4.1. in your lab book. Show the outline of the POSS print and mark on a few of the bright stars. Mark the position of the following objects on it.

1. Stars

a) The brighter a star is in the sky, the larger its image on the photograph will be. Would you expect, therefore, the image of a blue star to be larger or smaller on the blue prints than on the red prints?

b) Near the lower right part of the print 1099 there are two fairly bright stars that appear near each other in the sky. 30 Cygni is the star to the north and 31 Cygni is to the south. Which is the bluer of these stars?

c) Find and mark the location of another very blue and another very red star.

2. Planetary Nebula

A planetary nebula appears on print 1099. It contains ionized hydrogen ejected by a dying star, so you would expect its color to be red.

Search on the print of the appropriate color and give its position. Clue: it is small and round, with a sharp boundary.

Search for it on the print of the other color. What do you find? Explain how it is formed.

3. Globule

A globule is a very thick dust cloud, so small that it may soon collapse to form a new star. Since dust absorbs all light emitted by more distant stars and nebulae behind it what color will the globule appear on the prints?

Search on print E-754 for the tiniest dust cloud you can find and mark its position. The globule may look like a speck of dust on the print or a flaw in the film. How can you check that it is a real globule and not merely a flaw?

4. Reflection Nebula

A reflection nebula occurs when dust scatters light from a nearby star. This makes the star redder and the scattered light seems to come from an extended region surrounding the star. The same thing happens in our atmosphere, making our sky blue.

A reflection nebula appears in the right half of 0-754. Search for this reflection nebula, mark its position, and explain how it is formed.

5. Milky Way

The diagram given earlier shows roughly where the Milky Way is located. Now look on the red prints and compare the number of stars in the Milky Way (per square cm) with the number in the upper right part of print 1099. What do you find?

We believe that our Galaxy is a disk of billions of stars, and that most of these are situated in the direction of the Milky Way. Why, then do we not see the greatest number of stars along its central line?

We can make a very rough estimate of the number of stars in our galaxy by counting how many stars there are in a small area and then multiplying by how many small areas there are in the sky. Count the stars in a millimeter by a millimeter square and then multiply by 100 Million to find roughly how many stars there are in the Milky Way galaxy.

6. Dust Clouds

Two dust clouds appear on E-754 at the lower left and lower right. Each is a thick, opaque cloud. Given this information, which cloud is farther away? Explain your reasoning.

7. Miscellaneous

a) Look at E-1099 and E-754 together and notice how the long filamentary structures tend to curve and suggest they may be part of a circular structure with its center on the lower part of E-754. Although it is hard to see on the print, near the center is a group of stars known as the OB association Cygnus OB2. They are very strongly reddened by the interstellar dust between us and them and this dust has also dimmed their light. If this dust were absent, some of the stars would be among the brightest stars visible in the sky. Can you see this association? It is also interesting because there is a source of X-rays as well as a large, strong source of radio waves in the same directions which may have been left by a supernova.

b) Examine anything else that looks interesting and see what you can deduce about it from a comparison of the two prints or from a comparison with other nearby regions.

c) Imagine trying to give a name to each star in the upper right part of print 1099.

Web Site

`http://www.stsci.edu/resources/`

5 A STELLAR MASS FROM A VISUAL BINARY ORBIT

OBJECT

From the gravitational interaction of the stars in a visual binary we determine the mass of the stars.

THEORY

When two stars of masses m_1 and m_2 revolve around each other according to Newton's law of gravitation, they actually revolve around their common center of gravity; the two stars move in similar elliptic orbits with semi major axes a_1 and a_2 such that

$$m_1 a_1 = m_2 a_2 \tag{5.1}$$

The center of gravity of the pair is at one focus of each ellipse. When we observe a visual binary it is not at all easy to measure the absolute motions of the two components. Rather, one star (the brighter, but not necessarily the more massive) is named the primary, and the measurements are usually made of the position of the other star (the secondary) with respect to the primary. The secondary describes a similar elliptic orbit of semi-major axis $a = a_1 + a_2$ with the primary at one focus.

Figure 1 shows the orbit of the secondary star B relative to the primary star A. The "plane of the sky" is a plane through A at right angles to the line joining the observer to A. The line NN' is the line of nodes.

The orbit can be described fully by seven elements:

a The semi-major axis. If the distance to the system were known, this could be expressed in km. When it is not known, it is expressed in seconds of arc, meaning the angle the semi-major axis would subtend at the observer if the orbit were tilted about the line of nodes until it lay in the plane of the sky.

e The eccentricity.

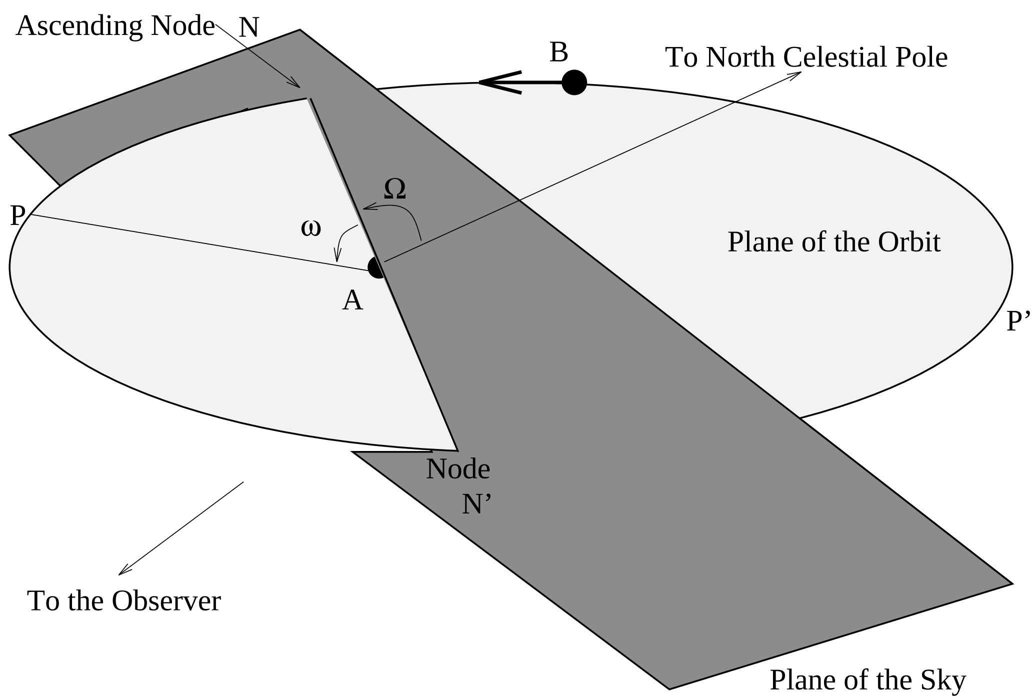


Figure 5.1: The elements of an orbit.

Ω The position angle of the nodal point. There are two nodes, N, and N'. As drawn, N is the ascending (approaching) node and N' is the descending (receding) node. The nodal point is that node whose position angle is less than 180^o, regardless of whether it is the ascending or descending node. The position angle is measured in the plane of the sky from the hour circle through A eastwards, and it lies in the range $0^o - 180^o$.

ω The argument of periastron. Measured in the plane of the orbit in the direction of motion of the secondary. It lies in the range $0^o - 360^o$ Periastron P is the point on the orbit closest to A; apastron P' is the point on the orbit furthest from A.

i The inclination of the orbit to the plane of the sky. It lies in the range $-180^o < i < 180^o$. The sign convention is as follows. If the nodal point is the ascending node, i is positive; otherwise it is negative. If the position angle of the secondary increases with time, $0 < |i| < 90^o$. If the position angle of the secondary decreases with time, $90^o < |i| < 180^o$. In Figure 1 the nodal point is the descending node, so that i is negative.

The position angle of the secondary is increasing with time so that $|i| < 90^o$. Special cases are: (a) The orbit is in the plane of the sky. In this case $i = 0$ or 180^o depending upon the direction of motion of the secondary. In neither event need i be signed. (b) The orbit is perpendicular to the plane of the sky. In this case the position angle of the secondary does not change with time (except by 180^o twice per period) and $i = +90^o$ or -90^o according to whether the nodal point is ascending or descending.

T Time of periastron passage.

P Period.

When a visual binary is observed, what is seen is not the true elliptic orbit, but its projection in the plane of the sky. The projection is still an ellipse, and the center of the true ellipse maps onto the center of the projected ellipse. However the foci of the true ellipse do not map onto the foci of the projected ellipse, nor do the major and minor axes. The primary star is not at the focus of the projected ellipse. Kepler's law of areas is applicable in both the true and the projected ellipse since all areas in the projected ellipse are reduced by the same factor $\cos i$.

OBSERVATIONS

The observations consist of a set of values of separation and position angles at different times. Five such observations are sufficient to determine the ellipse. In practice many more observations are used and a least squares solution is computed.

If we have some clear weather and Kruger 60 is above the horizon during your lab section, we will obtain a picture of it with our 0.5m telescope and CCD camera. It has a Right Ascension of 22:28:15 and a Declination of +57:43:09.

IMAGE RESTORATION

Because light is a wave, all pictures of stars are smeared by the telescope and camera optics. All pictures from the ground are smeared as well by the atmosphere. This makes it difficult to resolve fine details in the objects one views, such as close visual binary stars. We know that a star's image was an infinitesimal point that has been spread out by a certain function, due to the optics and the atmosphere. We call this function the point spread function or PSF. If we can find this function and invert it we should be able to recover all the detail in the original picture. In practice noise in the image will limit the usefulness of the techniques.

The Lucy algorithm (Lucy 1974 Astronomical Journal 79, 745) is contained in IRAF and we can use it to sharpen the images you have hopefully taken last week. The algorithm takes a lot of computation so we have cut a piece of the image containing the stars of interest. We need one star which we assume is single and use it to find the PSF and the other star is the visual binary, which we wish to resolve. This has been done for you and the files have been placed in the directory kruger60 and are called 1995k.fits for Kruger60 and 1995a.fits for star "a". The instructor will sign on to the computer and an xterm will be on the screen.

/astro/a200> **ls**

you will see a listing of the files and sub-directories already present.

Change directories to iraf by typing:

/astro/a200> **cd iraf**

and start IRAF by typing:

/astro/a200> **cl**

You should now have the "**cl**>" prompt on the screen. Change to your working directory by typing:

cl> **cd ../kruger60**

Type

cl> **ls**

to see what files reside in this directory. You should see 1995k.fits, and 1995a.fits. These files contain 21 pixel squares surrounding the stars Kruger60 and star "a". Let's take a look at these files using the routine **contour**.

cl> **epar contour**

and set the "*" parameters to match:

```
                              I R A F
               Image Reduction and Analysis Facility
PACKAGE = plot
   TASK = contour
```

```
image   =          1995k.fits  image or image section to be plotted      *
(floor  =               INDEF) minimum value to be contoured (INDEF for  min)
(ceiling=               INDEF) maximum value to be contoured (INDEF for max)
(zero   =                  0.) greyscale value of zero contour
(ncontou=                   0) number of contours to be drawn (0 for default)
(interva=                  0.) contour interval (0 for default)
(nhi    =                  -1) hi/low marking option: -1=omit, 0=mark h/l, 1=ma
(dashpat=                 528) bit pattern for generating dashed lines
(device =           stdgraph) output device
(title  =    kruger60 in 1995) optional title                            *
(preserv=                 yes) preserve aspect ratio of image?
(label  =                  no) label major contours with their values?   *
(fill   =                  no) fill viewport regardless of device aspect ratio?
(xres   =                  64) resolution in x
(yres   =                  64) resolution in y
(perimet=                 yes) draw labelled perimeter around plot?
(vx1    =                  0.) NDC viewport x1
(vx2    =                  0.) NDC viewport x2
(vy1    =                  0.) NDC viewport y1
(vy2    =                  0.) NDC viewport y2
(subsamp=                  no) Subsample (vs blockaverage) to decrease resoluti
(append =                  no) append to an old plot
(mode   =                  ql)
```

When you have made the changes type **:go** to make the routine execute. The ghostly graphics window will appear so paste it to the side of your text window and you will see that the star looks pretty round, but the contours are not exactly symmetrical.

A hard copy of this plot is made by typing:
re> **=gcur**

and then type a single = . In the graphics screen will be “snap - done” and your plot will appear on the printer. Type a **q** to exit the graphics window and the cursor will reappear in the text window after an annoying delay.

Plot the contours of the other star, changing the “image” and “title”.

Next we need to load the Space Telescope Science Institute routines with:
cl> **stsdas**

and the Analysis routines with:
st> **analysis**

and the image Restoration routines with:
an> **restore**

Now we need to set the "*" parameters for the lucy routine by:
re> **epar lucy**

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = restore
   TASK = lucy

input   =           1995k.fits  > Input image, blurred data              *
psf     =           1995a.fits  > PSF image                              *
output  =            out95.imh  > Output image, restored data            *
adu     =                  50.  > Conversion constant, electrons/DN      *
noise   =                  19.  > Additive/read-out noise, electrons     *
(niter  =                   99) > Maximum number of iterations           *
(limchis=                  0.1) > Limit of chi-squared for convergence   *
(model  =                     ) > Model image to be used as a first guess
(backgro=                    2) > Background image name or constant value *
(weight =                     ) > Weight image
(maskin =                     ) > Input mask image -- also set goodpixval
(goodpix=                    1) > Good pixels in mask identified by 1 or0
(nsigma =                   5.) > Sigma factor for masking negative pixels
(maskout=                     ) > Output mask image
(accel_m=                turbo) > acceleration method                    *
(xsizeou=                    0) > X dimension of output image
(ysizeou=                    0) > Y dimension of output image
(center =                  yes) > Center input data in output image
(nsave  =                    0) > Output every nsave iteration to  image_iter
(update =                    0) > Update output image every nsave iteration
(verbose=                  yes) > Print list of masked pixels, etc.
(mode   =                   al)
```

type **:go** when you have edited the parameters and the routine will execute for a while. When it finishes then use contour to see the sharpened result.
re> **contour out95.imh title=out95**

Make a hard copy of the plot with **=gcur** and write a few sentences comparing the before and after plots.

We have treated other pictures of Kruger 60 from other years in a similar manner and these will be given to you by the lab instructor.

Plotting the Orbit

Sky and Telescope Data

The Sky and Telescope reprint LE12 contains photographs of Kruger 60 from earlier in this century, when the two stars could be seen as two images. It also contains drawings from the 1970's when the stars were too close to be resolved in photographs. Measure the separation between the stars in millimeters and convert it to arc seconds, using the scale. Also measure the angle of the line connecting the stars to the North direction. Measure this position angle from the North to the East.

Plot these observations on a piece of circular graph paper.

Period

The period of the system can be most easily found from your plot of the position angles and separations, by finding two dates, when the points overlap in position angle. Estimate the period for this system. What is your uncertainty?

Center of Orbit

The center of the orbit can be found by averaging the separations and drawing a circle with that radius on a piece of transparency. The circle will be a little too big on the minor axis and a bit too small at the major axis. Mark on the center. Notice that the center does not lie at the origin of the graph paper. What object lies at the origin? Mark the periastron and apastron on the graph.

Semimajor Axis

The major axis connects the periastron to the apastron passing through the center and both foci. Mark the major axis on the graph and measure it's length in arc seconds.

Eccentricity

We can find the eccentricity of the orbit from your plot by measuring the distance from the center to the focus and dividing it by the distance from the center to the periastron. What is the uncertainty in the eccentricity?

Mass of System

Kepler's Law relates the total mass of the stars to the square of the Period P and the cube of Semimajor Axis A. In units of Solar Masses, Years and

Astronomical Units the relation is:

$$Mass = \frac{A^3}{P^2} \tag{5.2}$$

Since we have the Semimajor Axis in arc seconds we need to convert it to Astronomical Units, using the distance to Kruger 60 as measured by the Hipparcos satellite to be $4.01 \pm .05$ parsecs. Find the system mass and its uncertainty.

Inclination

We have assumed that the orbit is in the plane of the sky, so using diagrams comment on the effect of the orbital inclination on the apparent period, eccentricity, semimajor axis, and mass.

6 H-R DIAGRAM

> "We perceive the possibility of determining their forms, their distances, their sizes and their motions; whereas we shall never, by any means, be able to study their chemical composition, nor their mineralogic structure, and especially not the nature of organized creatures living on their surface."
>
> . . . Auguste Comte, 1835
>
> Cours de philosophie positive.

OBJECT

Construct a magnitude - spectral class plot (Hertzsprung-Russell diagram) of the Pleiades Cluster.

INTRODUCTION

In order to begin to understand the behavior, structure, and evolution of stars we seek to classify them according to properties which are relevant in terms of our physical theories and capable of being observed as directly as possible. These two criteria are not likely to be simultaneously met by the same properties, and so we must select the one most relevant and most convenient.

It is natural to choose stellar categories according to readily available observables. Standards must be defined (special stars named) which define each category. Then the observed characteristics must be linked with the physical parameters we wish to know. This last step is naturally the most speculative and subject to change as new physical theories are developed. Right away, we then see one advantage of choosing directly observable characteristics as indicators of stellar classification. These observables will remain unchanged, hence categories will not have to be redefined as physical theories change, and therefore the observational material will form a fixed body of data, unchanged by developments in theory.

With this notion in mind then we can approach the problem of stellar classification. We may classify stars in terms of their spatial characteristics (position, velocity), or we may classify them in terms of a property of their emitted radiation. In this exercise we will be concerned with classification schemes based on the visible light from stars. The simplest observable is of course the apparent luminosity of a star. By itself it is not of much value since it is not an intrinsic property of the star, but depends on the distance of the star from us. Accordingly if we know the distance, and hence the absolute magnitude, we have a parameter which allows stars to be simply categorized according to their brightness, or energy output.

In this exercise we shall bypass the distance problem by selecting a group of stars all at approximately the same distance from us. Then their relative apparent luminosities are an accurate representation of their relative intrinsic (or "absolute") luminosities. The group we shall use is the Pleiades open cluster. This cluster is visible to the naked eye in the winter sky as a tiny group of 6 or 7 stars. Telescope photographs show the Pleiades Cluster contains over one hundred stars.

Perhaps the next simplest property we may perceive of a star's light is its color, or gross spectral distribution. Already we have the basis for a simple two dimension array of stellar types, with stars placed into boxes according to their absolute luminosity and color. Note that even for a simple scheme such as this one, for purposes of classification nothing has been assumed about the connection between these observables and the fundamental physical quantities we wish to know, such as for example, temperature, or mass, or composition, et cetera. When we remember that bodies heated to different temperatures have different colors, we will presume that stellar color is in some way an indication of stellar surface temperature. But the exact connection between color and temperature need not, and cannot, be exactly stated in order to proceed with classification of stars.

The third easiest to determine property of starlight is its more detailed distribution over the visible spectrum. This is the property which has been used to establish most of the stellar classification schemes, and the one we shall use in this exercise.

In 1817 a Bavarian, Joseph Fraunhofer, announced the discovery of dark lines crossing the bright solar spectrum. Of the more than 500 lines he observed, he labeled the most prominent with the letters A to K, a designation they still retain. Fraunhofer used these lines chiefly as wavelength standards for his optical work. It was not until past the middle of the 19th century that spectrum analysis arose. It had been observed by several scientists that the Fraunhofer D line, which was double, coincided in wavelength with the double yellow line emitted by heated sodium vapour. It was concluded that this was strong evidence that sodium was present on the sun. Gustav Kirchoff (1824-1887) developed the physical theory necessary to interpret spectral lines in terms of the composition of the body of their origin. From that time on spectrum analysis became fundamental to astrophysics. Lines of many elements, hydrogen being of outstanding prominence, were subsequently identified. In this laboratory exercise we shall use spectral lines from several elements as classification criteria.

The first really comprehensive spectral classification was undertaken at Harvard in the first third of the 20th century, culminating in the "Henry Draper Catalogue" of nearly 400,000 stellar spectra. Stars were grouped according to the strengths of their hydrogen lines from spectra taken with objective prisms. Fundamentally then, this was a one dimensional classification scheme, types being labeled with the letters of the alphabet (A, B, C, D, E, etc.). When during the survey it was realized that increasing strength of hydrogen did not correspond to increasing temperature, but that the hydrogen lines were strongest at an intermediate temperature, the sequence of types was revised to correspond to a temperature sequence. The resulting alphabetical sequence, O, B, A, F, G, K, M (Oh Be A Fine Guy/Girl, Kiss Me) has subsequently remained unchanged. Here is a good example of the results of a physical theory - the theory relating spectral type to temperature - affecting the ordering of observational material. However the criteria for placing stars into specific spectral categories were not changed, already a dividend from the choice of observational characteristics, rather than derived physical parameters, as primary classification determinants.

As modern classification techniques have become refined, it has become necessary to use a more finely divided classification scheme. Each stellar type was subdivided into 10 sub-types, designated 0 through 9. Hence, for example, a star one-third the way between a B-star and an A-star is designated a B3-star.

The first graphical plots of stars classified according to the two criteria of luminosity and spectra were done in the first decade of the 20th Century by Ejnar Hertzsprung in Denmark and independently by Henry Norris Russell at Princeton. Such arrays are accordingly known as Hertzsprung-Russell (H-R) diagrams. They have proved extremely useful in studies of stellar populations and evolutionary behavior.

PROCEDURE

Table 6.1: Observations

Object	V (mag)	Flow Chart	Comparison	M_V (mag)	μ (mag)	D (pc)

1. Open the program labeled “Stellar Spectra” on your computer’s desktop.
2. Go to “File” then “Login”. Fill in the empty fields.
3. Go to “File” then “Run” then “Take Spectra”.
4. Click “Dome” and then “Tracking”.
5. Set coordinates to the Pleiades cluster:
   RA = 3h, 43m, 0s and Dec = 24°, 17′, 0″
6. Set “Slew Rate” to 16. (This is the quickest rate at which you can move the simulated telescope. Feel free to lower it at later points in the lab if you want the telescope to move more slowly.)
7. Recreate Table 6.1 in your lab notebook with seven columns: the object name, the apparent V-band magnitude V, the star’s classification by flow-chart, the star’s classification by comparison to other stars, the absolute V-band magnitude M_V, the distance modulus $\mu = V - M_V$, and the distance D. Leave 20 rows for recording data.
8. Open a table with the main spectral lines listed. To to this, click “File”, “Run”, “Classify Spectra”, then “File” and“Spectral Line Table”.

9. Use the N,W,S,E buttons to position the box over a star.

10. Click "Change View" and center the slit over the star.

11. Make sure that the star you chose is really a star by checking that its name listed under "Object" starts with "HD".

12. Click "Take Reading" then "Start/Resume Count". Click "Stop Count" once the signal to noise has reached at least 100.

13. Click "SAve" and name the file as the last three digits of the star's name.

14. Record the object's name and apparent V-band magnitude V in your table.

15. Classify the star based on the flow chart in Figure 6.1 and the line and spectra type descriptions below. You can tell which line is which using the table you opened in Step 8. Record your classification in your table.

16. Click "Change View" and repeat Steps 9 to 15 for at least 20 stars. (Don't worry about filling out the last four columns of the table for now.)

17. We can also classify our stars by comparing their spectra to those of stars that have already been classified. Click "File" then "Run" then "Classify Spectra". Now click "File" then "Unknown Spectrum" then "Saved Spectra" and open the first spectrum you saved.

18. Click "File" then "Atlas of Standard Spectra" then "Main Sequence". Use the "Up" and "Down" buttons to scroll through the standard spectra (shown in the top panel) and compare to your spectrum (shown in the middle panel). Note that the bottom panels shows the *residual*, or subtraction, between the standard spectrum and your spectrum. Classify your spectrum by comparison, choosing the standard spectrum that best matches your spectrum, with the smallest residuals. Record your comparison classification in your table.

19. Repeat Steps 17 and 18 for all twenty of your stars.

Table 6.2: Absolute Magnitudes of Main Sequence Stars, Luminosity Class V (from C.W. Allen, Astrophysical Quantities, The Athlone Press, London, 1973)

Spectral Type	Absolute Magnitude M_V (mag)
O5	-5.8
B0	-4.1
B5	-1.1
A0	+0.7
A5	+2.0
F0	+2.6
F5	+3.4
G0	+4.4
G5	+5.1
K0	+5.9
K5	+7.3
M0	+9.0
M5	+11.8
M8	+16.0

20. Use Table 6.2 to estimate the absolute magnitudes of your stars, based on the classification method you believe to be most reliable. Record the absolute magnitudes in your table.

21. Calculate the distance modulus $\mu = V - M_V$ for each star and record the value in your table. Use this formula:

$$D = 10^{0.2\mu+1} \tag{6.1}$$

to obtain distance D in parsecs from distance modulus μ for each star. Record the distances in your table.

22. Create an H-R diagram by plotting apparent magnitude versus spectral class, with spectral class arranged by temperature (OBAFGKM).

Line Descriptions

- The Balmer series of hydrogen. They are identified as Hβ, Hγ, Hδ, ϵ, and ζ. The distance between Hβ and Hγ is larger than the distance between Hγ, Hδ, etc. Hβ is at the redder (long wavelength) end of the spectrum.

- The pair of lines due to singly ionized calcium, called H and K by Fraunhofer when he was labelling the prominent dark lines he observed in the solar spectrum. The H line lies so close to the Balmer line Hϵ that they often cannot be separated.

- The so-called G band, identified by the letter G by Fraunhofer, and now known to be caused by the coincidence of atomic lines of iron and calcium.

- The neutral calcium line (CaI) at 4227$\AA$.

- The bands of titanium oxide at 4950$\AA$, 4760$\AA$, and 4585$\AA$ found in M-type stars.

Spectral Type **Defining Features**

B0 Hydrogen lines very narrow, HeI lines faint. Spectrum strong in ultraviolet

B2 Hydrogen lines narrow, HeI lines quite strong

B5 Hydrogen lines strong but narrow, HeI no longer visible

B8 Hydrogen lines very strong but narrow

A0 Hydrogen lines very strong and broad. "K" line weak or invisible

A2 Hydrogen lines still very strong. "K" line well visible

A5 "K" line strong, but weaker than the blend of "H" and Hϵ lines

F0 "K" line equal in strength to "H" + Hϵ blend. Hydrogen lines still fairly strong. G-band not yet visible

F2 "K" line stronger than "H" + Hϵ blend. G-band just becoming visible

F5 G-band well-pronounced but weaker than Hγ

F8 G-band equal to Hγ

G0 G-band stronger than Hγ. "H" and "K" very strong

G5 G-band strong. Hγ very faint. "H" and "K" very strong

K0 Owing to the large number of absorption lines there is a "break" in intensity at the G-band, the intensity of the spectrum to the blue being fainter

K2 G-band break pronounced. CaI (4227Å) well visible. Many lines may be visible between Hγ and Hδ

K5 G-band break very pronounced. CaI is prominent

M0 The first Ti0 bandhead at 4950$\AA$ is just visible

M2 The first Ti0 band is strong, the second bandhead at 4760$\AA$ is weak.

Sub groups not specifically listed also exist, and are gradations between those given.

NOTE: In astronomical notation, "I" after a chemical abbreviation for an element denotes a neutral ion, while "II" denotes a singly ionized atom, i.e. CaII is equivalent to Ca^+.

QUESTIONS

1. Discuss your H-R diagram. Do your stars form a main sequence? Do any lie off the main sequence? Why? Would you expect to see other parts of the H-R diagram such as red giants or white dwarfs?

2. Why is it acceptable to use the apparent magnitude instead of the absolute magnitude in your H-R diagram for these stars?

3. The sun is classified as a G2 dwarf. At what brightness (magnitude) would it appear if it were in the Pleiades? Could you see it with the naked eye?

4. What is the distance with uncertainty to the Pleiades?

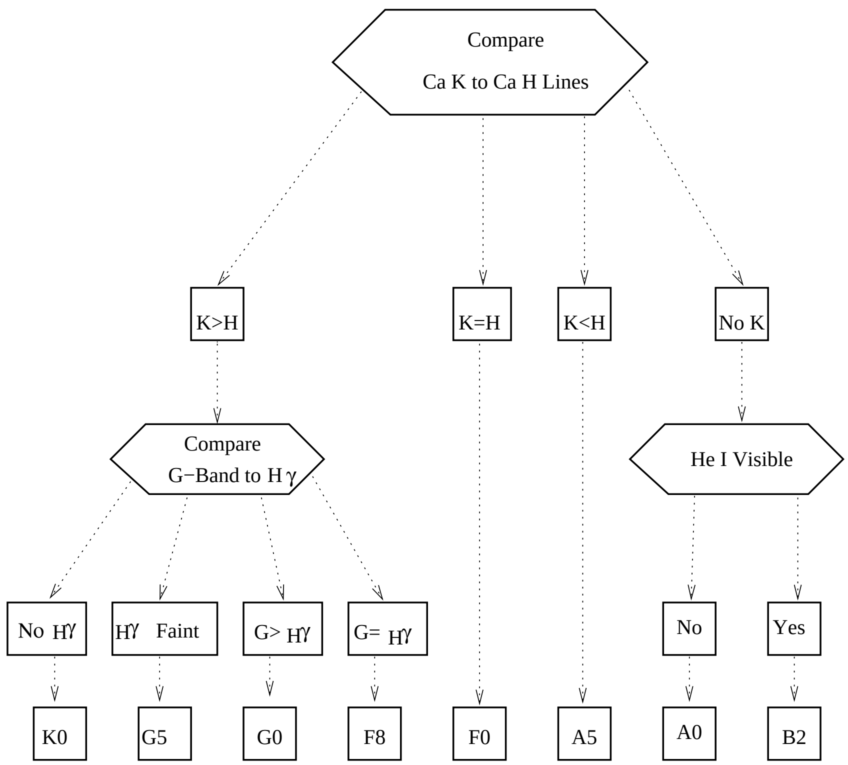


Figure 6.1: Flow Chart for Spectral Classification.

7 CHEMICAL ABUNDANCES OF ARCTURUS

OBJECTIVE

To familiarize students with stellar spectra and the methods for obtaining chemical abundances of stars.

INTRODUCTION

As discussed in previous labs, the strength of an observed spectral line (i.e. how dark the line appears) depends upon the number of absorbing atoms in the stellar atmosphere. For example, the Sun has a set of very strong sodium lines at 5890 Å; if the amount of sodium in the Sun was decreased, these lines would appear weaker. Thus, *observations of stellar spectra and measurements of the strengths of lines can provide information about the relative amount (or abundance) or certain elements in a star's atmosphere.* These abundances are typically reported on a logarithmic scale, relative to the amount of hydrogen or iron, relative to the Solar abundance.

Measurements of these chemical abundances are useful for many things, including *galactic chemical evolution* and *chemical tagging.* If the current atmospheric compositions of these stars reflect their initial compositions, then spectroscopic observations can provide information about the environment in which the star formed. Looking at these abundances in certain ways shows that stars of different ages from different environments have different chemistries. Figure 7.1 shows the [α/Fe] ratio (i.e. the logarithmic abundance of α-elements like Mg, Ca, and Ti relative to Fe, relative to the Sun) versus [Fe/H] (i.e. the logarithmic iron abundance relative to hydrogen, relative to the Sun). In this figure, the Sun would be located at $(0, 0)$. The oldest stars in a galaxy would have the lowest metallicity, and would be located on the lefthand side of the graph. As time goes on, stellar evolution will build up the metallicity of the gas in the interstellar medium, and younger stars will have higher metallicites.

Two key things are evident in Figure 7.1:

1. High mass (grey) and low mass (coloured) galaxies have different chemical enrichment histories (i.e. the coloured points are separated from the grey points).

2. In a given galaxy (e.g. the Milky Way, i.e. the grey points), lower metallicity stars have a higher relative amount of α-elements compared to iron; as the metallicity increases this ratio remains constant until it reaches a "knee" where the [α/Fe] ratio starts to decrease (this happens at around [Fe/H] ≈ -1.0 in the Milky Way).

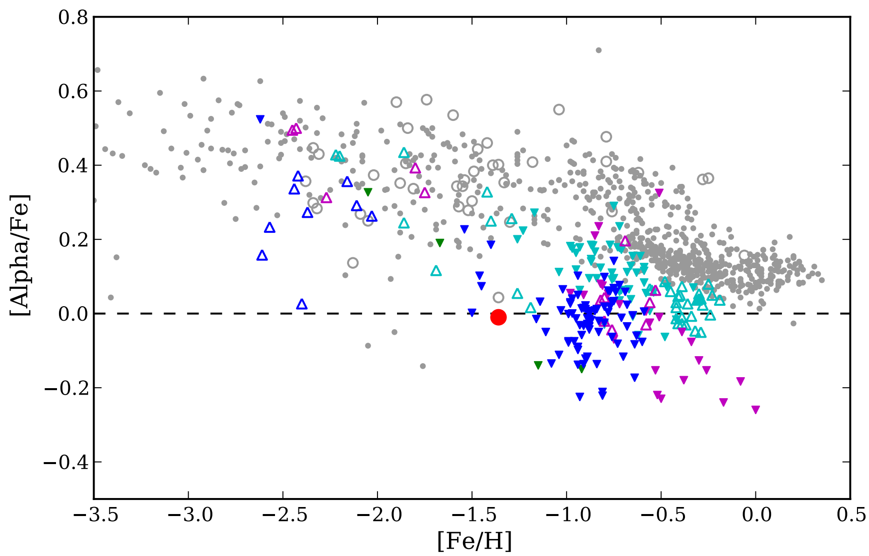


Figure 7.1: A plot of [α/Fe] abundances versus [Fe/H] for stars in the Milky Way (grey; as assembled by Venn et al. 2004) and those in dwarf galaxies (colours; as assembled by Sakari et al. 2011).

Both of these findings can be explained by considering how the α-elements and iron are formed. The α-elements are mainly formed in high-mass stars, and are distributed into the interstellar medium when these massive stars go supernovae. Core collapse supernovae also create iron, but in roughly the same proportions as the α-elements, regardless of metallicity. Thus, while core collapse supernovae are the only pollutants, the [α/Fe] ratio is roughly constantly over time. The massive stars that will eventually go supernovae are the first to evolve, and so they will contribute their chemical products to the interstellar medium first. As time goes on, however, lower mass stars can evolve into white dwarfs. If a white dwarf is in a binary, a Type Ia supernova can eventually occur. Once these Type Ia supernovae start to explode, a lot of iron will be produced, with virtually no α-elements, decreasing the $[\alpha/\mathrm{Fe}]$ ratio. This naturally explains the $[\alpha/\mathrm{Fe}]$ plateau that occurs at low metallicities, and the decrease that happens at metallicities higher than the "knee."

The location of the knee depends on how quickly a galaxy can form stars, pollute the interstellar medium, form more stars, etc. before its lower mass stars evolve. A high mass galaxy with a lot of gas (such as the Milky Way) will be able to form more stars in a given amount of time than a lower mass dwarf galaxy. Thus, a high mass galaxy will be able to enrich to a higher metallicity before Type Ia supernovae explode. Thus, dwarf galaxies (whose "knee" appears at a lower metallicity) will have stars with lower $[\alpha/\mathrm{Fe}]$ ratios than the Milky Way at a given metallicity (see Figure 7.1). This shows that chemical abundances can be used to trace a star's origin. If a star is observed in the Milky Way, chemical tagging can show whether it was born in the Milky Way, or whether it was accreted from a smaller satellite galaxy.

In order to determine the detailed chemical abundances of stars, high resolution spectra must be taken, and the strengths of spectral lines must be measured. The strength of a line is often characterized by its *equivalent width*, i.e. the width of a rectangle with a height equal to the continuum value and with the same area as the observed line (see Figure 7.2). These equivalent widths are often found by fitting the observed lines with Gaussian (normal) distributions. A Gaussian function is not an exact fit for a spectral line, but it should provide a good approximation for most lines.

Of course, the strength of a spectral line does not depend solely on the abundance of the absorbing element. Each line comes from a specific electronic transition. The Saha and Boltzmann equations clearly show that the relative numbers of electrons available to make these transitions depend on other parameters, such as temperature. Thus, the atmospheric parameters of the stars will affect the spectral lines as well. In order to convert the observed strengths of spectral lines into chemical abundances, we must first know these stellar atmospheric parameters. These atmospheric parameters can be estimated using the colours of stars. However, they are typically refined using the strengths of the iron lines.

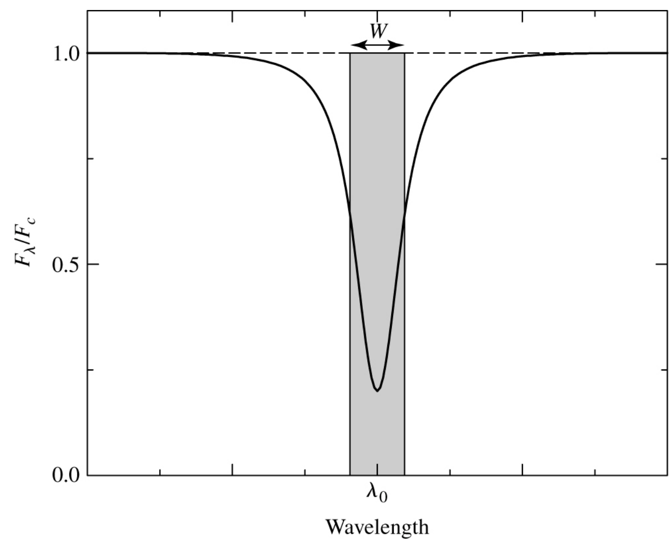


Figure 7.2: An illustration showing the definition of a spectral line's equivalent width Carroll & Ostlie (2006).

Iron lines are used because there are many of them in the visual part of stellar spectra. Of course, a star's atmosphere has a single iron abundance, so each spectral line should provide the same abundance. If the atmospheric parameters are incorrect, however, the abundances from all the lines will not be the same. With measurements of 50-100 lines, it is possible to investigate trends in iron abundance with, e.g., the strength of the line (to refine the microturbulence, ξ) or the excitation potential of the transition (to refine the temperature, $T_{\rm eff}$). By ensuring that there is no trend with any of these quantities, the atmospheric parameters can be deduced.

The purpose of this lab is to walk you through a full abundance analysis of the nearby (Milky Way) star Arcturus.

NOTE: Elements are divided into different *ionization states* depending on how many electrons have been ionized from the atom. A roman numeral "I" means that no electrons have been ionized, and that the atom is thus neutral (i.e. has no charge). A roman numeral “II” means that one electron has been ionized, etc. Elements of different ionization states (e.g. Fe I and Fe II) produce different spectral lines, yet the abundances determined from those lines should be equal. The ionization states are also occasionally given as decimals following the atomic number of an element, where “I” is .0, “II” is .1, etc. Thus, Fe I would be represented as 26.0.

EQUIPMENT

This lab will utilize models and programs from several different sources:

DAOSPEC: A line measurement program written by astronomers at the Dominion Astrophysical Observatory (Stetson & Pancino, 2008)

MARCS: Models of stellar atmospheres from the MARCS collaboration (e.g. Plez & Lambert 2002; Gustafsson et al. 2008)

MOOG 2010: A line analysis program to obtain chemical abundances (Sneden, 1973)

In addition, the Solar spectrum from the 2005 Kurucz Solar Atlas[2] and the Arcturus spectrum from the Arcturus Atlas[3] will also be used.

PROCEDURE

Step 0: Download and Check Files

The first step is to download all the files, uncompress them, and run a simple script to check if all files are in the correct location. Download the compressed file from the specified website. Move it to the home directory and uncompress it by typing:

```
> tar -xvf Spectroscopy.tar.gz
```

[2] `http://kurucz.harvard.edu/sun.html`
[3] `ftp://ftp.noao.edu/catalogs/arcturusatlas/`

Then move to the Spectroscopy directory and ensure that all the files are there, by typing:

```
> ./CheckMe
```

If there are missing files, notify the lab instructor.

Step 1: Examine the Spectra and Identify Features

You will be analysing two spectra: the Solar spectrum and the spectrum of the red giant Arcturus. Note that Arcturus is brighter, redder, and more metal-poor than the Sun.

First, open IRAF and look at the spectra with *splot* (a task in the imred and specred packages). (See the appendixes if you cannot remember how to do this.) Compare the two spectra by overplotting them (by typing "o" in the *splot* window, followed by the name of the spectrum to overplot).

Q: In general, how do the lines differ between the two spectra? Why might the strengths of the lines be different?

The darkest lines in the Solar spectrum are known as the Fraunhofer lines (shown in Table 7.1), and can often be seen without a telescope. Find several of these lines.

Q: What is different about the Fraunhofer lines from the other spectral lines in the Solar spectrum?

Step 2: Measure Some Spectral Lines

Locate the spectral lines shown in Table 7.2 in the Arcturus spectrum and measure the equivalent widths by fitting Gaussian profiles to the lines. With the cursor at the continuum position, type "h" followed by "a," "b," or "c" to fit the Gaussian to the left side, right side, or center of the line. Record your equivalent widths in the Table. Measure a couple of lines twice to see how close you are to your initial measurements. Be sure to re-measure at least one strong and one weak line.

Table 7.1: A selection of Fraunhofer lines

Wavelength (Å)	Designation	Element
4668.140	d	Iron
4861.340	F	Hydrogen (β)
4957.610	c	Iron
5167.330	b_4	Magnesium
5168.910	b_3	Iron
5172.700	b_2	Magnesium
5183.620	b_1	Magnesium
5270.390	E_2	Iron
5889.950	D_2	Sodium
5895.920	D_1	Sodium
6656.820	C	Hydrogen (α)

Table 7.2: Equivalent widths of notable spectral lines.

Wavelength (Å)	Element	EW1 (mÅ)	EW2 (mÅ)	ΔEW (mÅ)	DAOSPEC EW (mÅ)
6154.230	Na I				68.3
5711.090	Mg I				142.1
6156.030	Ca I				41.3
6508.120	Ti I				61.8
6588.320	Ni I				105.9
6496.910	Ba II				163.1

Table 7.3: Initial atmospheric parameters for Arcturus, based on its observed colours (from SIMBAD).

Temperature	$T_{\rm eff}$	4350 K
Surface gravity	$\log g$	1.70
Microturbulence	ξ	1.8 km/s

Q: Estimate the uncertainty in your EW measurement. Does this uncertainty change with the strength of the line? What do you find changes each time you measure the line (i.e. what seems to be the primary factor creating the uncertainty)?

Compare your equivalent widths to those measured by the program DAOSPEC (also shown in Table 7.2). Note that DAOSPEC detects all the lines in the spectrum, fits them simultaneously, and fits a continuum to the entire spectral region.

Q: Why do you think there could be differences between the measurement methods?

For the rest of the analysis we will use your Arcturus equivalent widths in Table 7.2 and the DAOSPEC equivalent widths for the other spectral lines. Open the file `ArcturusLines.moog` (e.g. in gedit) and input your equivalent widths. Note that the file is organized by element, with neutral iron (Fe I, shown as 26.0) lines given first.

Step 3: Find the Best-Fitting Model Atmosphere

The Introduction to this lab explains why Fe I lines are useful for determining the atmospheric parameters (i.e. the temperature, surface gravity, and microturbulence). To begin, we will approximate these parameters using Arcturus' observed colours[4] (shown in Table 7.3).

You will now open the line analysis program MOOG and find the abundances of the iron lines using these atmospheric parameters. Begin by check-

[4]Colours are from the SIMBAD database, at `http://simbad.u-strasbg.fr/simbad/`.

ing the file `abfind.par` to ensure that the model atmosphere is listed as "T4350g1.70". Now run MOOG by typing "MOOG" into the terminal, followed by "abfind.par". The program will show the abundances of all the Fe I lines. Hit ENTER until a graph pops up; this graph shows the abundances of the individual lines versus excitation potential, equivalent width, and wavelength. Fits to the points are also shown; the slopes of these fits are shown in the terminal.

Q: What are the slopes of the fits with these colour-based atmospheric parameters? Record all slopes in Table 7.4.

At the bottom of the screen you will also see the average Fe I abundance from all the lines, and the standard deviation in the abundances. If you hit ENTER again, you will then see the Fe II line abundances.

Q: What are the Fe I and Fe II abundances using these colour-based atmospheric parameters? Are the abundances equal (within the uncertainty)? Why should they be equal?

You can now change the model atmosphere by hitting the "m" key. You will have to type in the name of the new model atmosphere. The model atmospheres are named for the temperature and surface gravity, so that a model atmosphere with a temperature of 4300 K and a surface gravity of 1.50 would be named `T4300g1.50`. Increase the temperature of the model atmosphere by 100 K while keeping the colour-based gravity and microturbulence values. Then try increasing the gravity by 0.2 while keeping the temperture and microturbulence at the colour-based values.

Q: What happens to the slopes and iron abundances when the temperature and gravity are changed by 100 K and 0.2 dex, as described above?

Now return to the initial values and try changing the microturbulence by hitting the "v" key. The value (in km/s) needs to be entered.

Q: What happens to the slopes and iron abundances when the microturbulence is increased by 0.5 km/s?

Table 7.4: Slopes of excitation potential (EP), equivalent width (EW), and wavelength (λ) with Fe I abundance, and Fe I and Fe II abundances with various model atmospheres.

$T_{\rm eff}$ (K)	$\log g$	ξ (km/s)	EP Slope	EW Slope	λ Slope	Fe I $\log \epsilon$	Fe II $\log \epsilon$
4350	1.70	1.8					
4450	1.70	1.8					
4350	1.90	1.8					
4350	1.70	2.3					

Now try to find the best-fitting model atmosphere. Keep the surface gravity equal to the colour-based value (i.e. use $\log g = 1.70$). Adjust the temperature in increments of 50 K to minimize the slope of the Fe I abundances versus excitation potential. Adjust the microturbulence in increments of 0.1 km/s to minimize the slope of Fe I abundance versus equivalent width. Note that these two parameters are not independent; thus, you will have to adjust the two together. If you need more rows in your table use a separate sheet of paper.

Q: What are your best fitting values for the temperature and the microturbulence? Are the slopes perfectly flat? Are the Fe I and Fe II abundances equal? Estimate reasonable uncertainities for the temperature and microturbulence. How do your values agree with the colour-based values? Print out your final slopes by hitting the "h" key in MOOG.

Step 4: Find Chemical Abundances

With the correct model atmosphere, you can now find the other chemical abundances from MOOG. Besides iron (Fe, 26.0 and 26.1), you will also find the abundances of sodium (Na, i.e. 11.0), magnesium (Mg, 12.0), calcium (Ca, 20.0), titanium (Ti, 22.0), nickel (Ni, 28.0), and barium (Ba, 56.1). Ensure that the correct line list (`ArcturusLines.moog`, with your equivalent widths entered) and model atmosphere (with your final parameters from Step 3) are entered into `abfind.par`. Also ensure that you enter the correct microturbulence value when you start up MOOG.

After showing all the lines of a given element, MOOG presents the mean abundance (i.e. the average of all the individual line abundances). The errors shown in MOOG are the standard deviation, i.e. the line-to-line scatter. Calculate the uncertainty in the average abundance.

Q: What are the mean Arcturus abundances (and uncertainties)? Enter these $\log \epsilon_X$ values into Tables 7.5 and 7.6. Are the errors from MOOG random or systematic?

Of course, there are additional sources of uncertainty, notably the uncertainty in the equivalent widths and the uncertainty in the atmospheric parameters. You can estimate the uncertainties in the abundances caused by the equivalent widths by changing the equivalent width in the line list (`ArcturusLines.moog`). Use the uncertainty you calculated in Step 2 to determine the abundance difference. Then change the model atmosphere by your estimated uncertainties (from Step 4), and calculate the difference in abundance.

Q: What are the uncertainties in the abundances from equivalent width and atmospheric parameter uncertainties? Enter them into Table 7.5. For each source of error, discuss whether it is systematic or random.

ABUNDANCE QUESTIONS

1. The Solar abundances are also shown in Table 7.6. How do the Arcturus abundances (i.e. the $\log \epsilon_X$ values) compare to the Solar abundances? Do you find that Arcturus is more metal-poor or metal-rich than the Sun?

2. A star's "metallicity" is typically given by the amount of iron a star has relative to hydrogen, compared to the Sun. This value, [Fe/H], is just the difference between the iron abundance in the target star and the Solar iron abundance, i.e.

$$[\mathrm{Fe/H}] = \log \epsilon_{\mathrm{Fe}} - \log \epsilon_{\mathrm{Fe,Sun}} \tag{7.1}$$

   where $\log \epsilon_{\mathrm{Fe}}$ is the abundance you obtained from MOOG. Calculate [Fe/H] for Fe I and Fe II, and enter the values in Table 7.6.

3. Another useful measurement is to compare a star's abundance of an element X relative to the amount of Fe, relative to the Sun. This ratio is represented as [X/Fe], and can be calculated using the formula:

$$[\mathrm{X/Fe}] = \log \epsilon_{\mathrm{X}} - \log \epsilon_{\mathrm{X,Sun}} - [\mathrm{Fe/H}] \tag{7.2}$$

   where $\log \epsilon_X$ is the abundance of element X. (**Remember that [Fe/H] may be negative!**) Calculate these values and record them in Table 7.6. What do these values tell you about the relative amounts of X to

Table 7.5: Arcturus abundances and abundance uncertainties.

Element	Avg Abundance $\log \epsilon_X$	$\Delta \log \epsilon_X$ Δ EW	$\Delta \log \epsilon_X$ ΔT	$\Delta \log \epsilon_X$ $\Delta \xi$
Fe I				
Fe II				
Na I				
Mg I				
Ca I				
Ti I				
Ni I				
Ba II				

Table 7.6: Solar and Arcturus abundances.

Element	Solar $\log \epsilon_X$	Arcturus $\log \epsilon_X$	[Fe/H]	[X/Fe]
Fe I	7.52			—
Fe II	7.52			—
Na I	6.24		—	
Mg I	7.60		—	
Ca I	6.34		—	
Ti I	4.95		—	
Ni I	6.22		—	
Ba II	2.18		—	

Fe, as compared to the Sun?

4. Mg, Ca, and Ti are special elements known as α-elements. These elements are expected to form in core-collapse supernovae from massive stars. Average their [X/Fe] values together to find an average [α/Fe] value. Does this value tell you that Arcturus has more or less α-elements relative to iron than the Sun?

5. Plot the [α/Fe] and [Fe/H] values on a graph with other Milky Way stars by executing the script `PlotMe.py` (by typing `python PlotMe.py` into the terminal). Enter your [α/Fe] and [Fe/H] values when prompted, as well as the errors associated with each value. Do your Arcturus values agree with the other Milky Way stars?

6. What does Arcturus' position in this plot tell you about the environment in which it formed compared to the environment in which the Sun formed?

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8 SIZE OF THE GALAXY

> "In studying the distribution of globular star clusters, I was led some years ago to consider the circumstance that stars near the Sun fail to show the same galactic circle as that outlined by Milky Way star clouds. Further, when the globular star clusters appeared to show that the galactic center is at a great distance from the Sun in the direction of Sagittarius, and yet the evidence from star counts seemed to indicate that the Sun is near the center of the stellar system, the question arose as to whether the star distribution in the solar vicinity might not be only a local phenomenon; our Sun – might it not be near the center of a subsystem, but remote from the real galactic center?"
>
> ...Harlow Shapley. 1930
>
> Flights from Chaos, p. 123.

INTRODUCTION

Globular clusters are compact stellar systems containing between tens of thousands and millions of stars. They are spherical in shape and show practically no evidence of gas or dust. Their stars appear a bit reddish. Of the more than one hundred globular clusters known, many are very small or far away and cannot be resolved into individual stars.

In 1895 S. I. Bailey, working at Harvard College Observatory, noticed that three globular clusters contained variable stars. Soon thirty other globular clusters were also found to contain variables. Their light curves identified them as RR Lyrae variables, which was interesting, since it related stars in these unusual objects to field stars in the solar neighborhood.

If the intrinsic brightness of a star is known a priori, then by measuring its apparent brightness and comparing the two brightnesses, that star's distance may be calculated. The relationship between intrinsic magnitude (M), apparent magnitude (m), and distance (d), in parsecs is given by:

$$m - M = 5 \log d - 5 \tag{8.1}$$

With a CCD camera and telescope the apparent brightness of a star is easily measured. The problem then is to determine the intrinsic brightness of the star. Variable stars are very important in this context since the nature of their variability allows us to recognize them as specific stellar types. For the class of variable stars known as Cepheids there is a relatively well defined relationship between the period of light variation and the intrinsic luminosity of the star. Therefore, if the shape of a light curve identifies a star as an "Cepheid" and its period is measured, then its absolute magnitude is known, and its distance may be calculated.

Members of the sub-group of Cepheid variable stars known as "RR Lyrae" stars all seem to have nearly the same intrinsic brightness even though their periods cover a range between 0.5 days and 1.0 days. The amplitude of the brightness changes is about half a magnitude in the visible part of the spectrum. The problem of establishing the absolute magnitude of RR Lyrae stars has been pursued since the beginning of last century. Fitting cluster main-sequences to a main sequence of stars with accurately known distances is now the usual way of determining the absolute magnitude of RR Lyrae stars: the currently accepted value is +0.7.

In this laboratory exercise light curves of some variable stars in a globular cluster are obtained. These curves enable us

(i) to identify the variables as RR Lyrae types, so that we know their absolute magnitudes, and

(ii) to find their average apparent magnitudes and hence, their distances.

The System of the Globular Clusters

In the years 1916-1917 Harlow Shapley had been taking photographs of globular clusters at Mt. Wilson with the 60" reflector. He noticed the marked concentration of these clusters toward the region of the sky near Sagittarius, although there were none near the middle of the Milky Way band itself.

Shapley was in a good position to estimate the distance to those clusters in which he could detect Cepheids and measure their periods. This he did for the brighter clusters. In the fainter clusters the Cepheids are below the threshold of detection. But these faint clusters also appeared smaller, thus supporting the hunch that they were of similar construction to the brighter ones but simply at greater distances.

The assumption of similar essence could be used to convert the brightness and size data into distance data. Eventually, Shapley accumulated sufficient data to construct a picture of the distribution of the globular clusters with respect to the Milky Way band. The model comprised a more or less spherical distribution of clusters centered far off in the direction of Sagittarius, at a distance estimated by Shapley to be about 16 kpc. The fact that most clusters appear to be in one region of the sky demonstrates that we are outside most of the spherical distribution. In computing distances Shapley assumed no absorption of the light of the Cepheids or the whole clusters. If absorbing material were present, making stars appear fainter, it would have led Shapley to overestimate the distances, so we may say that the upper limit of the distance to the center of the globular cluster system was 16 kpc. This was a real revolution in conception of the size of our stellar system. Supposing the clusters to have a symmetrical distribution with respect to the Milky Way stars, we would be in a flat, circular system at least tens of thousands of parsecs in diameter.

Finding the Distance to the Center of the Globular Cluster System

In this exercise we shall compute the distance to the center of the Milky Way globular cluster system using a technique very similar to that used by Shapley. Instead of the 86 clusters Shapley used, we shall rely on only about ten, but that is enough to give a reasonable estimate of the distance. Since, in Shapley's words, "it appears to be a tenable hypothesis that the supersystem of globular clusters is coextensive with the Galaxy itself," then by finding the distance to the center of the globular cluster system, we shall also find the distance to the center of the galaxy.

We shall choose a section of sky near to the direction of the apparent center of the globular cluster system in Sagittarius. In this area of about $15^o \times 15^o$ (centered on right ascension 19^h00^m and declination -30^o) there are ten globular clusters. We shall find the distance to the center of the group by averaging them. In doing so we must make several assumptions:

a) The angular size of a cluster is inversely proportional to its distance. This is tantamount to presuming that all clusters are of more or less the same intrinsic size.

b) We see in this limited region a representative selection of globular clusters, both near and far.

c) There is not such a large amount of absorption of light between us and the clusters that it would obscure the most distant ones, or seriously affect their apparent sizes.

Calculating a Weighted Mean

When we take a photograph of a section of sky, the volume of space recorded in the picture increases very rapidly with distance (see Figure 8.1). In the first kiloparsec of distance from us a narrow wedge of space (volume A) is photographed. At a great distance away, however, an extra kiloparsec of distance includes a much larger slice of space (volume B). Clearly we should expect to see more clusters in volume B than in volume A just because of its greater size. That means we shall see an anomalously great number of distant clusters and an anomalously small number of nearby clusters.

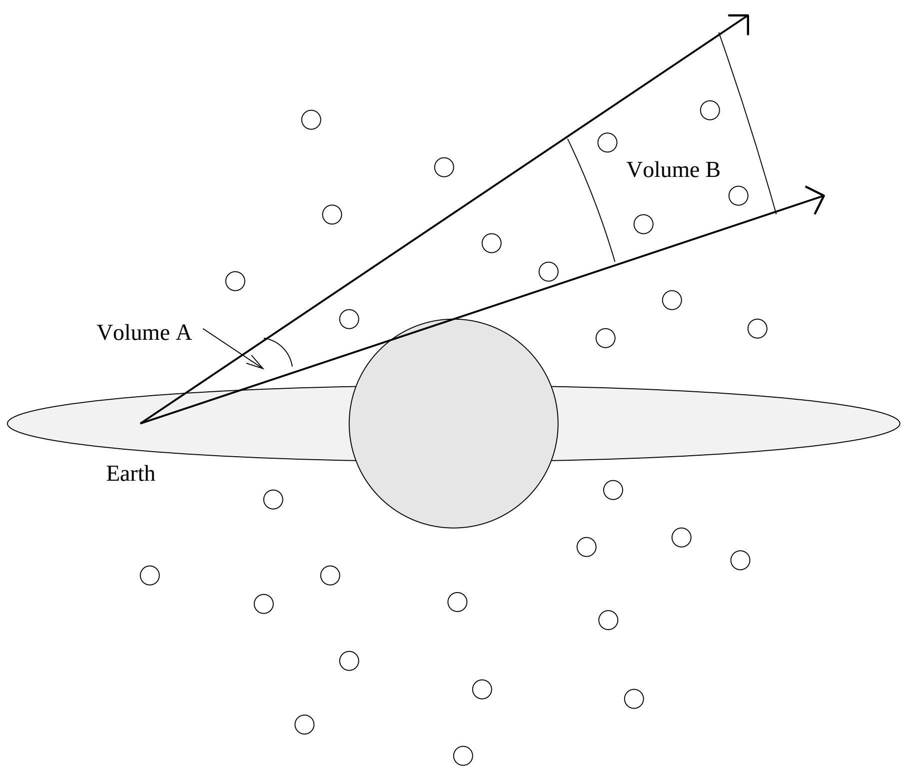

Figure 8.1: Globular Cluster Distribution about the Galaxy.

The wedge represents the region of clusters seen in a photograph. We must account for this effect before averaging cluster distances, or else the extra distant clusters will yield a lopsided result. The area of the beam covered by the photograph increases as the square of the distance, and this is the correction factor needed.

Let R_i be the distance of the i^{th} cluster, and θ_i its angular diameter. If all clusters are assumed to be of about the same linear size, then

$$\theta_i = \frac{k}{R_i} \tag{8.2}$$

where k is a constant of proportionality. If there were no effect of broadening the beam of sight with distance, the average distance, $\overline{R}$, of N clusters would be given by

$$\overline{R} = \frac{R_1 + R_2 + R_3 + \ldots + R_N}{1 + 1 + 1 + \ldots + 1} = \frac{R_1 + R_2 + R_3 + \ldots + R_N}{N} \tag{8.3}$$

We must however put in a correction factor, W_i, for each cluster which tells how many times that cluster must be counted in order to account for the fact that too few clusters are seen close by. In other words, the factor W_i effectively augments the number of nearby clusters to simulate the case of a non-divergent, cylindrical beam of sight.

Now the average distance is given by

$$\overline{R} = \frac{W_1 R_1 + W_2 R_2 + \ldots + W_N R_N}{W_1 + W_2 + \ldots + W_N} = \frac{\sum_{i=1}^{N} W_i R_i}{\sum_{i=1}^{N} W_i} \tag{8.4}$$

If, for example, $W_1 = 2$, then cluster number 1 in effect gets counted twice, which accounts for the fact that if the beam had been wider in the region of cluster number 1 it probably would have intercepted an additional cluster. Note that the factor $W_1 = 2$ would also appear in the denominator, since if the cluster number 1 is counted twice, then the total number of clusters, which is the sum in the denominator, must also be augmented by 1.

Remember that we pointed out that the area of the beam increases with the square of the distance. So the correction factor must compensate for this effect by decreasing with the square of the distance.

$$W_i \propto \frac{1}{R_i^2} \tag{8.5}$$

Thus $\overline{R}$ becomes,

$$\overline{R} = \frac{\frac{R_1}{R_1^2} + \frac{R_2}{R_2^2} + \ldots + \frac{R_N}{R_N^2}}{\frac{1}{R_1^2} + \frac{1}{R_2^2} + \ldots + \frac{1}{R_N^2}} \tag{8.6}$$

$$= \frac{\frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_N}}{\frac{1}{R_1^2} + \frac{1}{R_2^2} + \ldots + \frac{1}{R_N^2}} = \frac{\sum_{i=1}^{N} \frac{1}{R_i}}{\sum_{i=1}^{N} \frac{1}{R_i^2}} \tag{8.7}$$

Finally we want to change from R_i to θ_i; after all θ_i is what we measure from our photograph.

$$\overline{R} = \frac{\frac{\theta_1}{K} + \frac{\theta_2}{K} + \ldots + \frac{\theta_N}{K}}{\frac{\theta_1^2}{k^2} + \frac{\theta_2^2}{K^2} + \ldots + \frac{\theta_N^2}{K^2}} \tag{8.8}$$

$$\overline{R} = K\frac{\theta_1 + \theta_2 + \ldots + \theta_N}{\theta_1^2 + \theta_2^2 + \ldots + \theta_N^2} = K\frac{\sum_{i=1}^{N} \theta_i}{\sum_{i=1}^{N} \theta_i^2} \tag{8.9}$$

The only step left is to evaluate the constant K. It arises because we do not yet know the actual relationship between distance and angular size. If we knew the actual distance to one cluster, and could measure its apparent size, then we would have K.

The globular cluster M3 contains RR Lyrae variable stars, and is close enough to determine their periods and magnitudes. In the first part of the procedure you will obtain a value for R_{M3}. Then you will measure the angular diameter θ_{M3} of M3. Then

$$K = R_{M3}\theta_{M3}, \tag{8.10}$$

and the equation becomes,

$$\overline{R} = R_{M3}\theta_{M3}\frac{\theta_1 + \theta_2 + \ldots + \theta_N}{\theta_1^2 + \theta_2^2 + \ldots + \theta_N^2}. \tag{8.11}$$

EQUIPMENT

- Images of the globular cluster M3 taken by Dan Caton of Appalachian State University.
- Images of each of the ten globular clusters in Sagittarius taken from the Digital Sky Survey

PROCEDURE

First we need to find the distance to M3. Some of the RR Lyrae stars in M3 are marked in Figure 8.2. We have many pictures of M3 all taken during one night. We want to measure the brightness of each RR Lyrae star on each frame. Then we want to plot the brightness of each RR Lyrae as a function of time and find its average magnitude. By comparing each RR Lyrae star's average apparent magnitude to its absolute magnitude we can find its distance.

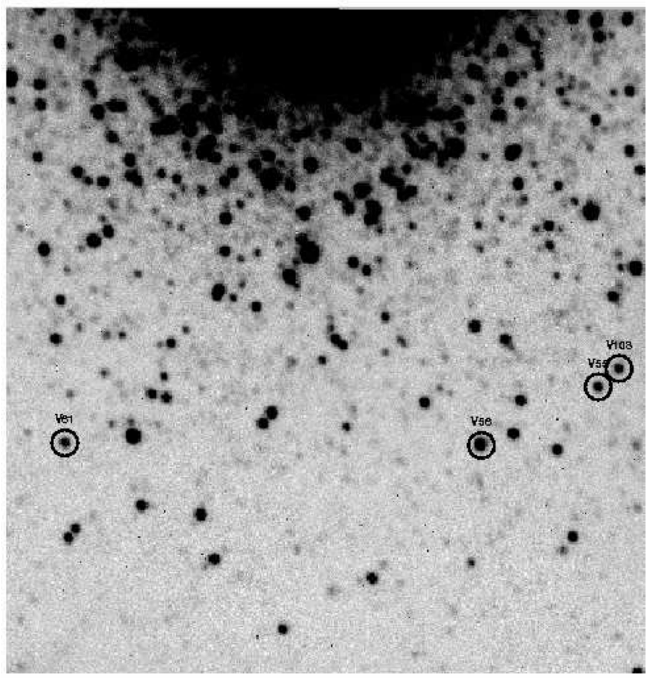

Figure 8.2: Globular Cluster M3 with some RR Lyrae stars indicated.

First we need to get to the right directory. Type:

/astro/a200>**cd**

to go to your home directory.

/astro/a200>**pwd**

to confirm that you are in the directory /astro/a200/. Type

/astro/a200>**ls**

to get a listing of all the files and directories. Bring up the SAOimage and run it as a background task by typing

/astro/a200>**ds9 &**

To use **IRAF** to display your images we need to change directories to the iraf directory, type

/astro/a200>**cd iraf**

Then to start iraf type

/astro/a200>**cl**

The screen will clear and the message of the day will appear. Type
cl> **cd ../m3**
to change directory up to the m3 directory. Type **ls** to list the files in this directory and there should be a lot of .fits files. If not check with the instructor. We need to increase the size of the image buffer to hold such large images with the command:
cl> **set stdimage=imt4096**
now display the first image with:
cl> **display 015005.fits 1**
Does it look much like the finder chart?

Photometry of RR Lyrae Stars

Use the finder chart above to locate the RR Lyrae stars in this image. We will be performing aperture photometry on these stars so we need to list their X, Y positions into a file. This can be done using the **rimcursor** task in IRAF:
cl> **rimcursor > rrlyraes**
Position the cursor over an RR Lyrae and hit the SPACE bar. This will put the (X,Y) coordinates of the RR Lyrae star into the file rrlyraes. Repeat for the other variables. Quit **rimcursor** by typing CTRL-Z in the DS9 window. Take a look your file to make sure you haven't made any mistakes by typing:
cl> **cat rrlyraes**
This command should output 4 lines with the first two columns giving the (X,Y) coordinates of the RR Lyrae stars, while the last two are not important

and can be safely ignored.

Now, perform aperture photometry on these stars by using the **qphot** task. The **qphot** task can be accessed by typing:
cl> **digiphot**
di> **apphot**
Aperture photometry works by placing an aperture of a specified radius over each star and summing up the total amount of flux within that aperture from both the star and the sky. To compensate for the unwanted flux from the sky we must use an annulus surrounding the star to determine the the mean sky value per pixel. This is subsequently subtracted from each pixel contained within the star aperture in order to get an accurate measurement of the true brightness of the star. The few pieces of information that the **qphot** task needs to know are: what images to work with, where the stars are located in the image (from the file called "rrlyraes"), how large an area to search for the center of the star (approximately 5 pixels in this case), how large a radius of the aperture (bigger than FWHM or 20 pixels in this case), and how large a sky annulus (inner radius of 20 and width of 50 pixels). These are all specified by editing the parameters of **qphot**; changing only the ones marked with an "*". If you put in a value where you need a blank, type a [space bar] and then an [enter].
ap> **epar qphot**

```
                               I R A F
                    Image Reduction and Analysis Facility
PACKAGE = apphot
   TASK = qphot

image   =              *.fits  The input image(s)                     *
cbox    =                  5.  The centering box width in pixels       *
annulus =                 20.  The inner radius of sky annulus in pixels *
dannulus=                 50.  The width of the sky annulus in pixels   *
aperture=                  20  The list of photometry apertures         *
(coords =            rrlyraes) The input coordinate file(s) (default:*.coo.?)*
(output =             default) The output photometry file(s) (default: *.mag.?)
(plotfil=                    ) The output plot metacode file
(zmag   =               27.93) The zero point of the magnitude scale    *
(exposur=                    ) The exposure time image header keyword
(airmass=                    ) The airmass image header keyword
(filter =                    ) The filter image header keyword
(obstime=                  UT) The time of observation image header keyword *
```

```
(epadu  =                    1.) The instrument gain in e-/ADU
(interac=                    no) Interactive mode ?                    *
(radplot=                    no) Plot the radial profiles in interactive mode ?
(icomman=                      ) Image cursor: [x y wcs] key [cmd]
(gcomman=                      ) Graphics cursor: [x y wcs] key [cmd]
(wcsin  =              )_.wcsin) The input coordinate system
(logical,tv,physical
(wcsout =             )_.wcsout) The output coordinate system
(logical,tv,physica
(cache  =              )_.cache) Cache input image pixels in memory ?
(verbose=            )_.verbose) Print messages in non-interactive mode ?
(graphic=           )_.graphics) Graphics device
(display=            )_.display) Display device
(mode   =                    ql)
```

Type **:go** to perform aperture photometry on the RR Lyrae stars in all 53 images. This may take a while and you may see some warnings about keywords which you can safely ignore. Once this has finished type **ls** to see the files which **qphot** has created for you. For each image there will be a "image-number.fits.mag.1" file which contains the photometry of the RR Lyraes.

Light Curves

Next we want to build a light curve for each of the RR Lyraes. This can be done by extracting the observations times and magnitudes from all the "image-number.fits.mag.1" files.

ap > **txdump *.mag.1 "otime,mag" "id=1"**

A bunch of numbers will scroll down the screen with the first column listing the time each image was taken in Universal Time (note the time format is hours) while the second column lists the magnitude of the RR Lyrae in each image. Now this information isn't much good to you unless you put it into a file which can be read by a plotting program so type:

ap > **txdump *.mag.1 "otime,mag" "id=1" > var1**

Repeat this command for the remaining RR Lyraes by typing "**e**" and pushing the up arrow to scroll back up the list of IRAF commands. Ensure that you change from **id=1** and **var1** to **id=2** and **var2** etc., but leave *.mag.1 as *.mag.1 for all images. You will now have files that contain the information needed to plot a light curve for each RR Lyrae. We can see the light curves by using **xmgr** so type:

ap > **!xmgr &**

Once the **xmgr** window appears select *File* and then the option *Read* then the option *Sets*. Click on the file *Var1* and the button *Autoscale on Read* and the click *OK* **ONCE!!!!**. You should see the light curve appear in the plot window but it will be upside down. To invert the y-axis click to *Data*, then *Graph Operations*, and then *Invert/Flip axis* and clicking the *Invert Y* button. Add a title to your plot by going to *Plot* and then *Titles*. Double click the y-axis to label it and the x-axis. Finally print out your light curve by going to *File* and *Print*. Now clear the current plot by going to *Data* and selecting *Set operations*. Select the option *Kill all* to erase the light curve but keep the plot window and axes there. Create light curves for the other RR Lyraes by repeating the above method and don't forget to change the title! Once you are finished plotting the light curves exit **xmgr** by going to *File* and *Exit*

Estimate the mean magnitude for each RR Lyrae by using the maximum and minimum magnitudes. What is your uncertainty in the mean magnitude? Finally, you are ready to determine the distance to the globular cluster M3 by using:

$$m_v - M_v = 5 \log D - 5$$

Assume the mean *absolute* magnitude for RR Lyraes is $+0.7 \pm 0.1$ magnitudes. Find the distance to M3 and its uncertainty.

Direction of the Center of the Galaxy

To find the direction to the center of the Milky Way galaxy, plot the positions of the globular clusters on the map of the sky. There are more than a hundred clusters so you will need to plot only about every fifth cluster. What is the Right Ascension and Declination of the center of the galaxy?

Angular Size of Globular Clusters

Now that we know the direction of the center of the galaxy we can find the distance by measuring the distance to each of the globulars in that direction and averaging. We can get the distance to any globular cluster by assuming it is the same physical size as M3 and measuring its angular size and scaling its distance from M3's distance.

Ideally, we would choose a group of globular clusters which are situated exactly in the direction of the galaxy's center, but these clusters are obscured by dust. Close to the direction of the center of the galaxy the Lick print ($19^h 00^m, +15^o$), contains ten globular clusters.

We have downloaded images of each of these globular clusters from the Digital Sky Survey and we can display then with a program called **skycat**. First change to the directory where the images are stored by typing:
ap > **cd ../globs/**

Then start up the program:
ap > **!skycat &**

Once the **skycat** window appears go to the *File* and *Open* and select the file "m3.fits". After a few seconds the image will appear in the window. Measure the angular size of the cluster by clicking and holding the right button of the mouse. Drag the mouse across the plot window and you will notice that a right triangle is formed with the length of each size measured in units of *arc minutes' : arc seconds"*. Measure the diameter of M3 using this technique and make sure to record your results in units of *arc seconds* along with a reasonable uncertainty. Now repeat this to measure the sizes of the 10 other globular clusters in the list with "NGC" designations (ignore m15.fits). Choose a suitable criterion for measuring the sizes, such as the diameter of the brightest and densest part of the cluster image and make sure to adhere to the same criterion for all the other cluster. Record your measurements in a table in arc seconds, remembering that there are 60 arc seconds in an arc minute. Quit the skycat program when you are finished.

Distance to Center of Galaxy

Tabulate the values of the previous step, and use them to find the distance to the center of the galaxy $\overline{R}$ using for R_{M3} the distance to M3 you obtained from the variable stars. Calculate the value of the sum of the angular diameters and the sum of the squares of the angular diameters. Compare your value of the distance to the center of the galaxy with the Hipparcos satellite value of 8600pc.

Mass of Our Galaxy

The sun orbits the center of the galaxy with a velocity of about $220 \pm 30 \frac{km}{sec}$. We can estimate this velocity by measuring the apparent velocity of nearby galaxies or by finding the star with the largest velocity and assuming that it is bound to the galaxy. Assuming a circular orbit, find the period of the sun's orbit around the center of the galaxy in years. Also, find the mass of the galaxy in solar masses.

QUESTIONS

1. Why is the choice of criterion for measuring apparent diameters unimportant, as long as you stick to the same criterion once it is chosen?
2. What would be the effect of missing entirely one or two very distant, and hence small, clusters?
3. What would be the effect on $\overline{R}$ of there being by chance one more large, close cluster included in your sample?
4. Globular clusters are not actually all of the same size (thereby contradicting assumption (a)). How do you think this may affect your results?
5. What do you think of just using a singular cluster (M3) for "calibration" of the results: i.e., for finding K? Suppose M3 were an unusually small cluster, what would this do to your result for R?

9 ROTATION OF THE EARTH

Measure the rotation period of the Earth with respect to the sun, and also with respect to the stars (i.e. compare the lengths of the solar and sidereal days).

You may use any technique(s) that you wish for these labs, provided that they involve direct measurement and observation. Extra marks will be given for demonstrations of imagination and ingenuity. Your final write-up should include a full discussion of the objective, theory, your chosen experimental technique, a discussion of sources of error, and a comparison with "theoretical prediction".

10 THE PROPER MOTION OF BARNARD'S STAR

OBJECTIVE

To determine the proper motion of Barnard's star using two images taken with the Climenhaga telescope and CCD Camera.

INTRODUCTION

Barnard's star has the largest known proper motion (10".30 per year) of any star in the sky and is the nearest known subdwarf (old, low metallicity star). Because of its rapid change in position, the proper motion of Barnard's star can be determined through comparison of its position on CCD images taken only a year or so apart. For this lab, we will use images taken with the .5-m Climenhaga telescope and the package IRAF to confirm its proper motion. The first image is located in the directory **/astro/a200a/Barnard** as **Barnard14jul94.fits**. We will be using your current image of Barnard's star as our second frame.

PROCEDURE

Data Gathering

Go to the telescope, take the covers off, turn on the CCD camera, monitor, computer, etc. Set the filter to **C C**. Using the finder chart provided by your instructor, and following the observing steps necessary to set the Right Ascension, Declination and Sidereal Time on the telescope, locate Barnard's star. Take a 30 second exposure. What is the ADU level for the image of the star? Save your image to disk and note the exposure number.

Be sure to summarize how you obtained these images at the telescope. Include as much detail as you can as to how we set the Right Ascension and Declination on the telescope, how we located Barnard's star, the gain used, how we determined the exposure time, etc.

Data Analysis

Getting Started

Your instructor will log you into one of the a200 directories. If you type in
/astro/a200> **ls**

you will see a listing of the files and sub-directories already present.

To see what is in an ASCII file type
/astro/a200> **cat** *filename*
Change directories to iraf by typing:
/astro/a200> **cd iraf**

The Smithsonian Astrophysical Observatory (SAO) astronomer M Van-Hilst wrote the program SAOimage to display CCD frames. The new improved version is called "Deep Space Nine". This program will "pipe" data both to and from IRAF. Bring up the SAOimage by typing:
/astro/a200> **ds9 &**

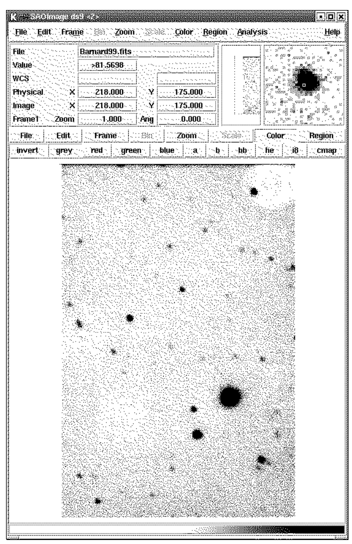

Figure 10.1: Deep Space Nine showing Barnard's star.

and start IRAF by typing:
/astro/a200> **cl**

You should now have the "**cl**>" prompt on the screen. Change to your working directory by typing:
cl> **cd ../Barnard**

Type
cl> **ls**

to see what files reside in this directory. You should see the Flexible Image Transport files with the extension ".fits" and maybe the old IRAF images files which have a header (.imh) and pixel (.pix) files. If not, check with your instructor.

Determining the Coordinate Shift

Now you need to get the information for the rest of this lab. To begin we need to see the picture we took of Barnard's star so while in IRAF, type the following:
cl> **display Barnard14jul94 1**
to run the *display* task.
Display your recent image by typing
cl> **display Barnard15oct96 1**

Visually examine the copies of both images carefully and locate 6-8 stars (excluding Barnard's star) which can be unambiguously identified on both frames. Number these stars on your copy to avoid confusion later. This labeled print should be included in your lab write up.

You must now redisplay the 1994 image. You are getting lots of practice.

We now want to find the centers of the chosen stars. IRAF has a task called *imexamine* which will do this for us. It will precisely find the center of a star on which you put the cursor and it will record the x and y positions in file along with a lot of other information. It will call the x and y positions rows and columns. First reset imexam's parameters to their default values:
cl> **unlearn imexamine**

Now, edit the *ed parameters for the task *imexamine* by typing:
cl> **epar imexamine**
and changing your parameters to the following:

Parameters for imexamine

```
                               I R A F
                    Image Reduction and Analysis Facility
PACKAGE = tv
   TASK = imexamine

input   =  Barnard14jul94.fits  images to be examined           *
(output =                     ) output root image name
(ncoutpu=                  101) Number of columns in image output
(nloutpu=                  101) Number of lines in image output
frame   =                    1  display frame                   *
image   =                       image name
(logfile=               barn94) logfile                         *
(keeplog=                  yes) log output results              *
(defkey =                kl006) default key for cursor list input
(autored=                  yes) automatically redraw graph
(allfram=                  yes) use all frames for displaying new images
(nframes=                    0) number of display frames (0 to autosense)
(ncstat =                   10) number of columns for statistics
(nlstat =                   10) number of lines for statistics
(graphcu=                     ) graphics cursor input
(imagecu=                     ) image display cursor input
(wcs    =              logical) Coordinate system
(xformat=                     ) X axis coordinate format
(yformat=                     ) Y axis coordinate format
(graphic=            stdgraph) graphics device
(display= display(image='$1',frame=$2)) display command template
(use_dis=                  yes) enable direct display interaction
(mode   =                   ql)
```

Specifying a "logfile" (e.g., Barn94 or Barn96 and "keeplog = yes" will give you a file of all coordinates.

Type in:

:go

to save the changes and execute the task.

Place the cursor on the stars you identified earlier and hit the "**a**" key. What quantities are being determined? You are interested in the **X** and **Y** coordinates for all stars, excluding Barnard's star. Do each star once and record the order that you do them in. Typing **q** in the SAO tool saves your work and exits back to command mode. If you type the **q** in the text window nothing good happens and IRAF ignores almost everything you type. Check the file with:

cl> **cat barn94**

We want to get the x and y star positions for the 1996 image so display it.

cl> **display Barnard15oct96 1**

Now, again *epar* the parameters for *imexamine* and change the logfile name. Produce a file of all of the **X** and **Y** coordinates for your chosen stars and not Barnard's star. Do the stars in the same order.

This has created two files **barn94** and **barn96** which contain the x and y positions of the stars which hopefully have not moved. We want to check this and to find the shift of the origin from 1994 to 1996. Since the stars have kept the same position relative to one another, the difference between the 1994 x position and the 1996 x position should be the same for each of the stars. Should the y differences be the same - as each other - as the x differences. Check the files with:

cl> **cat barn96**

To extract the x (column 1) and y (column 2) positions of the stars from the barn94 and barn96 files we use the IRAF task *field*.

cl> **field barn94 1,2**

will list the x and y values on your screen and

cl> **field barn94 1,2 > xy94**

will store them in a file *xy94*. Do the same thing for the 1996 data and check that the files look correct with

cl> **cat xy94**

If there are mistakes in your files you can repair them using the simplest UNIX editor called PICO. To edit the file xy94

cl> **!pico xy94**

and all the editing commands you need are displayed on the bottom lines of the window.

We can now join the files together with the IRAF task *join* and create a new file xy9496 with the x and y positions for 1994 and 1996 in four columns one line for each star.

cl> **epar join**

and setting the parameters to match:

```
                          I R A F
             Image Reduction and Analysis Facility
PACKAGE = proto
```

```
   TASK = joinlines

list1   =            xy94,xy96  List of input files to be joined  *
list2   =                       List of input files to be joined  *
(output =               xy9496) Output file                       *
(delim  =                     ) Delimiter between file lines
(missing=              Missing) Marker for missing lines
(maxchar=                  161) Maximum number of output charactersper line
(shortes=                  yes) Quit at end of shortest file?
(verbose=                  yes) Print verbose warnings?
(mode   =                   ql)
```

Check the file with:
cl> **cat xy9496**

We now need to find the differences in x and y between 1994 and 1996 for each of the stars. The differences should be constant because the stars have not moved much in two years. *AWK* is a UNIX program which can do anything including taking the differences between columns of numbers and printing them out. To subtract the 1994 x value (column 1) from the 1996 x value (column 3) Try:
cl> **!awk '{print $1,$3,$3-$1 }' xy9496**

to display x values for 1994 and 1996 and the differences. If there are any obvious errors then fix them with the editor.
cl> **!awk '{print $3-$1 }' xy9496 > dx96-94**

is used to store the differences in file dx96-94. Run AWK on columns $4 and $2 to find the differences in y.

Check that the numbers are in the file with:
cl> **cat dx96-94**

We now want to average the differences in x and y so:
cl> **cat dx96-94 | average**
cl> **cat dy96-94 | average**

will get the averages of the x and y differences and give the standard deviations and the number of background stars. The standard deviations give the uncertainty you should expect to get for any of your measurements including Barnard's star. This gives you an estimate for the uncertainty in your measurements.

Determining the Proper Motion

Now go back and using *imexam* measure Barnard's star on both the 1994 and 1996 frames. If you now add the average differences, you found from your star measurements you can find out where Barnard's star should have been if it had not moved. Do that and subtract it from the 1996 position of Barnard's star to find the proper motion in x and y.

Since all measurements are in **X** and **Y** pixel positions, we need to convert the **X** and **Y** components to arcseconds. We know that the CCD chip has 384 pixels in the north-south direction each of which is 23×10^{-6} m square. Our 0.5 meter telescope has a focal length of 5.25 meters and so the scale is about 0.869 arc seconds per pixel. Find the components of the proper motion in arc seconds and the total proper motion in arc seconds per year. How do your results compare with the proper motion of 10.357704 arc seconds per year measured by the Hipparcos satellite?

What is the size of the major sources of error in this lab?

There is no need to print out your data files. However, your lab write up should give the names and contents of all files generated in this exercise.

11 STAR COUNTS

OBJECTIVE

To determine the number of stars in the sky at each magnitude interval.

INTRODUCTION

Obviously when you look at the sky you see a few bright stars and lots of faint ones. How many **more** faint ones is an interesting question. We can simplify things by assuming that all the stars are the same brightness and are spread through space uniformly. Then the bright stars are close and the faint ones are more distant. The farther you look the more volume you see and so you would expect to see more faint stars.

In fact we know that the volume "V" is a function of the distance "r" to which we can see:

$$V = \frac{4}{3}\pi r^3 \tag{11.1}$$

If the stars are distributed uniformly in space with a density "ρ", then the number of stars "N" out to a distance "r" is just:

$$N = \rho \times V \tag{11.2}$$

$$\log N = \log \rho + \log V \tag{11.3}$$

$$\log N = \log (\rho\frac{4}{3}\pi) + 3\log r \tag{11.4}$$

If there is no absorption of the star light by dust, the distance modulus relates the apparent brightness or magnitude "m" of a star, its intrinsic brightness or absolute magnitude "M", and its distance "r":

$$m - M = 5\log r - 5 \tag{11.5}$$

$$\log r = 0.2m - 0.2M + 1 \tag{11.6}$$

So combining the equations to find the number of stars brighter than a certain magnitude as a function of apparent magnitude gives:

$$\log N = K + 0.6m \tag{11.7}$$

where we combined all the constants into a constant "K". This is a nice theoretical prediction that we can easily test. All we need to do is to take a picture of the sky and measure the brightness of all the stars. A histogram plot of the log of the number of stars as a function of magnitude should then have a slope of 0.6.

PROCEDURE

To Get a Picture of the Sky

Note $\Longrightarrow$ often the observations are made one week and analyzed the next week.

We have a very nice digital camera model ST-8 made by the Santa Barbara Instrument Group. The detector is a CCD Integrated Circuit with 1530X1020 pixels each 9 microns in size. We can bin the pixels together to have 765X510 each 18 microns or bin by 3 to get 510X340-27 micron pixels. The CCD is cooled to reduce the noise caused by dark current. A computer controls the camera and is used to save the data. To get a picture you will need to go to the roof, turn on the CCD camera, monitor, computer, etc. The camera has been fitted with a very wide angle lens to include a large area of the sky. Point the camera to a part of the sky that you can recognize, such as the little dipper. Take a 30 second exposure making sure that the brightest stars are exposed to about the full well of the CCD = 65536ADU. Save your image to disk and note the exposure number.

Be sure to summarize how you obtained these images at the telescope. Include as much detail as you can as to how we set the binning, gain used, how we determined the exposure time, etc.

Data Analysis

Getting Started

Your instructor will log you into one of the a200 directories. The operating system is LINUX and only a very few of the commands will be used. If you type in
/astro/a200> **ls**

you will see a listing of the files and sub-directories already present.
To see what is in an ASCII file, type
/astro/a200> **cat** *filename*
Change directories to the iraf directory by typing:
/astro/a200> **cd iraf**

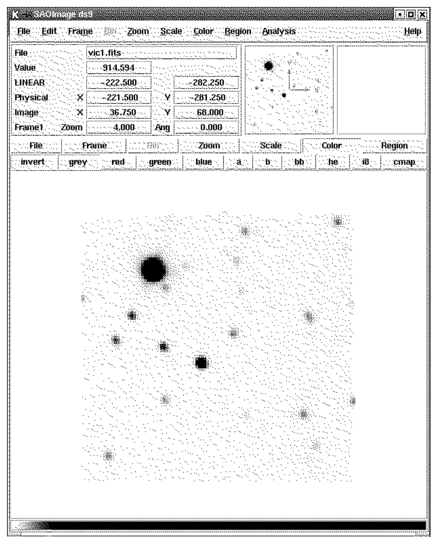

Figure 11.1:

The Smithsonian Astrophysical Observatory (SAO) astronomer M. Van-Hilst wrote the program SAOimage to display CCD frames. The new improved SAOimage program is called "Deep Space Nine". This program will "pipe" data both to and from IRAF. As in previous labs, bring up the DS9 version of SAOimage by typing:
/astro/a200> **ds9 &**
and start IRAF by typing:
/astro/a200> **cl**
You should now have the "**cl**>" prompt on the screen. Change to your working directory by typing:
cl> **cd ../counts**
Type
cl> **ls**

to see what files reside in this directory. You should see the fits (.fit) files which contain both header and pixel information. If not, check with your instructor.

Viewing the Header

To see the "Header" information which usually includes the object's name, the exposure time etc. type:
cl> **imhead pol3906.fit**

Viewing the Image

Now you need to see your image, which we will call pol3906.fit, but you should use your own image. Type:
cl> **display pol3906.fit 1**
to run the *display* task.

If the image is reversed right to left then recopy the file with:
cl> **imcopy rightleft.imh**[−∗, ∗] **leftright.imh**

to make it left to right. Or more easily just click on the [zoom] and [invert y] on the DS9 image viewer.

Turn the stars to black and the sky to white by clicking on the top [color] and [invert colormap]. Print a copy of this image by clicking on [file] and [print].

Visually examine the copy of your image carefully and locate 6-8 stars which can be unambiguously identified on your frames. Number these stars on your copy to avoid confusion. This labeled print should be included in your lab write up.

Finding the Size of a Star

Measuring the brightness of the stars individually would take a long time since we need to measure a thousand stars. Luckily there is a computer program written by Peter Stetson of the DAO included in IRAF that will go through a CCD frame and find all the stars. It basically works by finding all the groups of pixels that are significantly brighter than the surrounding pixels. All we need to do then is to find the size of a typical star and define "significantly".

We now want to find the size of the chosen star's images. IRAF has a task called *imexamine* which will do this for us. It will precisely find the center of

a star on which you put the cursor and it will record the x and y positions in file along with a lot of other information. Now, edit the parameters for the task *imexamine* by typing:
cl> **epar imexamine**
and changing the parameters with an * to the following:

Parameters for imexamine

```
                    Image Reduction and Analysis Facility
PACKAGE = tv
   TASK = imexamine

input   =        pol3906.fits  images to be examined                *
(output =                    ) output root image name
(ncoutpu=                 101) Number of columns in image output
(nloutpu=                 101) Number of lines in image output
frame   =                   1  display frame
image   =                      image name
(logfile=                    ) logfile
(keeplog=                  no) log output results                   *
(defkey =                   a) default key for cursor list input
(autored=                 yes) automatically redraw graph
(allfram=                 yes) use all frames for displaying new images
(nframes=                   0) number of display frames (0 to autosense)
(ncstat =                  10) number of columns for statistics
(nlstat =                  10) number of lines for statistics
(graphcu=                    ) graphics cursor input
(imagecu=                    ) image display cursor input
(wcs    =             logical) Coordinate system
(xformat=                    ) X axis coordinate format
(yformat=                    ) Y axis coordinate format
(graphic=            stdgraph) graphics device
(display= display(image='$1',frame=$2)) display command template
(use_dis=                 yes) enable direct display interaction
(mode   =                  ql)
```

Type in:
:go
to save the changes and execute the task.

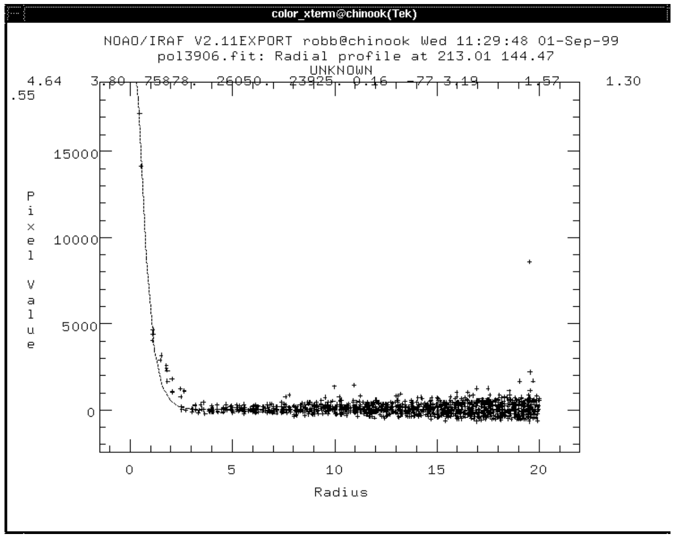

Figure 11.2:

Place the cursor on the stars you identified earlier and hit the "**r**" key. This will spawn a new window with the intensity on the y axis and the distance from the center of the star on the x axis. Notice that the intensity is large on the left at the center of the star and decreases to the right as you get away from the center of the star. We want to measure the "Full Width at Half Maximum" (FWHM) so put the cursor on a star and type the "**a**" key. The FWHM will be calculated three different ways and it does not matter which one you use. Do a few stars and record the FWHM.

We also need to know how noisy the background is so put the cursor on a blank area and type the "**m**" key. The mean and standard deviation will be printed in the text window. Do this for a couple of blank areas and record an average standard deviation.

As before, typing **q** in the SAO tool exits back to command mode. If you type the **q** in the text window nothing good happens and IRAF ignores almost everything you type.

Finding the Stars

We need to find the stars in the image before we measure the brightness of them. To find them we need to describe a star in terms of its size or Full Width at Half Maximum Intensity (FWHM). That way the finding algorithm

will not think a cosmic ray or flaw is a star. Datapars describes the star.
cl> **noao**
no> **digiphot**
di> **daophot**
da> **epar datapars**
and changing the "*" parameters in the following to the values you found using imexamine:

Parameters for datapars

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = daophot
   TASK = datapars

(scale  =                   1.) Image scale in units per pixel
(fwhmpsf=                   1.5) FWHM of the PSF in scale units       *
(emissio=                  yes) Features are positive ?
(sigma  =                  75.) Standard deviation of background in counts*
(datamin=                   1.) Minimum good data value                 *
(datamax=               65536.) Maximum good data value                 *
(noise  =              poisson) Noise model
(ccdread=                     ) CCD readout noise image header keyword
(gain   =                     ) CCD gain image header keyword
(readnoi=                   0.) CCD readout noise in electrons
(epadu  =                   1.) Gain in electrons per count
(exposur=                     ) Exposure time image header keyword
(airmass=                     ) Airmass image header keyword
(filter =                     ) Filter image header keyword
(obstime=                     ) Time of observation image header keyword
(itime  =                   1.) Exposure time
(xairmas=                INDEF) Airmass
(ifilter=                INDEF) Filter
(otime  =                INDEF) Time of observation
(mode   =                   ql)
($nargs =                    0)
```

To exit datapars type:
:qw

We also need to tell the finding algorithm how faint the stars are that we are interested in. We want to measure stars that are really faint, but we do not want to measure fluctuations in the background, thinking that they are stars. To set the faint limit we use the standard deviation of the background.

If the background is about 100 electrons then the standard deviation will be 10 electrons and 68% of the pixels will be between 90 and 110. 95% of the pixels will be between 80 and 120 or plus or minus two standard deviations. So if we set the faint limit to 2 standard deviations above the noise 5% of our "stars" are actually noise spikes. To be very conservative we can use 4 standard deviations, and 99.99% of the found stars are stars.

There should be nothing to change here but you should check.

da> **epar findpars**

and changing your parameters to the following:

Parameters for findpars

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = daophot
   TASK = findpars

(thresho=                    4.) Threshold in sigma for feature detection  *
(nsigma =                   1.5) Width of convolution kernel in sigma
(ratio  =                    1.) Ratio of minor to major axis of Gaussian kernel
(theta  =                    0.) Position angle of major axis of Gaussian kernel
(sharplo=                   0.2) Lower bound on sharpness for feature detection
(sharphi=                    1.) Upper bound on sharpness for  feature detection
(roundlo=                   -1.) Lower bound on roundness for feature detection
(roundhi=                    1.) Upper bound on roundness for feature detection
(mkdetec=                   yes) Mark detections on the image display ?
(mode   =                    ql)
($nargs =                     0)
```

To quit findpars and save the changes use:

:qw

We have an IRAF task that will go through your frame and find all the stars called DAOFIND. Here we only need to define, which frame we are dealing with.

da> **epar daofind**

and changing your parameters to the following:

Parameters for daofind

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = daophot
```

```
   TASK = daofind

image   =          pol3906.fit  Input image(s)                      *
output  =              default  Output coordinate file(s) (default:
image.coo.?)
(starmap=                     ) Output density enhancement image(s)
(skymap =                     ) Output sky image(s)
(datapar=                     ) Data dependent parameters
(findpar=                     ) Object detection parameters
(boundar=              nearest) Boundary extension(constant|nearest|reflect|wra
(constan=                   0.) Constant for boundary extension
(interac=                   no) Interactive mode ?
(icomman=                     ) Image cursor: [x y wcs] key [cmd]
(gcomman=                     ) Graphics cursor: [x y wcs] key [cmd]
(wcsout =           )_.wcsout) The output coordinate system
(logical,tv,physica
(cache  =            )_.cache) Cache the image pixels ?
(verify =           )_.verify) Verify critical daofind parameters ?
(update =           )_.update) Update critical daofind parameters ?
(verbose=          )_.verbose) Print daofind messages ?
(graphic=         )_.graphics) Graphics device
(display=          )_.display) Display device
(mode   =                  ql)
```

To exit this editing and make the task go, type:

:go

DAOFIND has also calculated the magnitudes, and it will write them to the screen and also put them in the file "pol3906.fit.coo.1" or what ever you called it. To see what is in the file try:

da> **cat pol3906.fit.coo.1**

We need to get the magnitudes out of the pol3906.fit.coo.1 file, so use "fields" to get the third field, which contains our magnitudes.

da> **fields pol3906.fit.coo.1 3**

We can then store the magnitudes in a file named "findmags" for instance.

da> **fields pol3906.fit.coo.1 3 > findmags**

da> **cat findmags**

will convince us that the correct numbers are recorded.

Making the Histogram

Now we need to plot the number of stars in each magnitude bin. We need to load two new packages.
da> **stsdas**
st> **stplot**

The "Histogram" task will sort the magnitudes into bins and plot them.
st> **epar histogram**
and changing your parameters to the following:

Parameters for histogram

```
                                 I R A F
                    Image Reduction and Analysis Facility
PACKAGE = stplot
   TASK = histogram

input   =            findmags  Input table or image or text file       *
(colname=                   1) Name of column to use if input is table

(nbins  =                  10) Number of histogram bins                *
(z1     =               INDEF) Minimum bin value
(z2     =               INDEF) Maximum bin value
(listout=                  no) Print histogram?                        *
(title  =         pol3906.fit) Title for plot                          *
(xlabel =                mags) Title for x axis                        *
(ylabel =               Count) Title for y xaxis                       *
(logplot=                 yes) Plot histogram with log y axis          *
(fulline=                 yes) Draw histogram lines to base of plot?   *
(cumulat=                 yes) Calculate cumulative histogram?         *

(dvpar  =                    ) Device parameters pset

(Version=              2Feb96) Date of installation
(mode   =                  al)
```

Hopefully the histogram has a nice straight relation for a least the middle of the plot. The bright stars (small numbers) will be few so there will be lots of noise at that end. The faint star end may turn over since there will too few detected. Check with the instructor at this point to make sure the data are okay.

When you are happy with your plot
st> = **gcur**

will give us the graphics cursor and then typing an "=" in the graphics window will get a hard copy of the plot. It will say "snap-done" in the graphics window when it is done. Then type a "q" and the cursor will return to the text window after a minute or so.

Find the Slope

It would be nice to get a fit to the straight part of the curve, so that we can compare it to the theoretical value. The task histogram will output the magnitude of a bin and the number in the bin by changing the listout parameter to "yes". We do not always have to "epar" a task to change a parameter; we can do it on the command line.
st> **histogram listout=yes**
It will prompt you for the file name and then output the magnitude number values. try:
st> **histogram findmags listout=yes**
and it will not prompt for the file name.
st> **histogram findmags listout=yes > magn**
will redirect the output to a file called magn.

To find the log of the number of stars we can use awk. AWK is a programming language available for UNIX systems for free from the "Free Software Foundation". It is useful for "simple data-reformatting jobs with just a few lines of code." Here we use awk to print column 1 and the log of column two but we need to multiply it by 0.4343 to convert it to a log to base ten.
st> **!awk '{print$1,0.4343*log($2)}' magn**
will print the magnitude and the log of the number of stars. To save it in a file try:
st> **!awk '{print$1,0.4343*log($2)}' magn > maglogn**
Now we need to get rid of the first few points and maybe the last few points because they are not on the line.
st> **!pico maglogn**
to edit the file. The edit commands are the listed along the bottom of the screen.

Then do the fit using the IRAF task polyfit.
st> **epar poly**

Parameters for polyfit

```
                                I R A F
                  Image Reduction and Analysis Facility
PACKAGE = utilities
   TASK = polyfit

input   =             maglogn  input files                   *
order   =                   1  order of polynomial           *
(weighti=             uniform) Type of weighting
(instrumental|uniform|statisti
(verbose=                 yes) list calculated fit to data
(listdat=                  no) list X-Y pairs only
(mode   =                  ql)
```

Poly will output the intercept and the slope with their uncertainty below the values. It will then give chi sqr: ftest: etc.

Is your slope equal to 0.6. Is it within the uncertainty in the slope?

Generalize to the whole sky

To find the area of the sky that you have surveyed just measure with a ruler the distance between two bright stars on the print of your field. Then measure the distance between the same two stars in a star atlas in degrees. This will give you the scale of your print so you can find the length and width of the print in degrees and the area in square degrees.

The magnitude zero point can be estimated by knowing the apparent magnitude of the brightest star on our picture. Then just relabel the histogram plot such that the first bin is the right magnitude.

You should get approximately 1 fourth magnitude star per one hundred square degrees (More in the Milky Way and fewer at the galactic poles).

Discussion

Most parts of the sky will give a significantly smaller slope than 0.6. If you can not think of two reasons why this would be, review the assumptions in the theory section. Explain which reason applies to your area. Check with others in the class and see if you all have the same reason.

Bonus

This same technique of counting the number of stars in each brightness bin can be applied to many different situations. For instance the distance to the Gamma Ray Bursters has been settled using this method without knowing anything about how the bursts are produced. The relation for the Gamma Ray Bursters (GRB's) has a slope of 0.6 everywhere in the sky. There is no concentration towards the Galactic Plane, Andromeda Galaxy or the Virgo Cluster. Explain how this limits the distance to the GRB's.

12 HST OBSERVATIONS OF IC4182

OBJECTIVE

CCD frames containing images from the Hubble Space Telescope will be analyzed to determine the periods of some Cepheid Variable stars in the galaxy IC4182. These periods will then be used to determine the distance to this galaxy.

INTRODUCTION

(This paragraph has been adapted from the Sky and Telescope lab on Cepheid Variables and the Cosmic Distance Scale.) Cepheid stars are variable stars which change in brightness with periods from 1 to 100 days. Some of these supergiant stars are more than 10,000 times as luminous as our sun and thus can be seen at great distances, being recognizable in the nearer galaxies. The Cepheids played a key role in the early years of this century in providing proof that there are galaxies other than our own. The first known Cepheid was δ Cephei, discovered in 1784 by an English amateur astronomer, John Goodricke. About 1879, A. Ritter theorized that the light variations of these stars are due to pulsations, the star alternately expanding and contracting. Later astronomers verified this idea by spectroscopic observations.

One of the key projects of the Hubble Space Telescope was to monitor Cepheid Variables in distant galaxies. This monitoring can take place for galaxies at much greater distances than those reachable from ground-based telescopes. We will be examining Cepheids located in just part of the galaxy IC 4182. IC 4182 is a Sdm galaxy at high Galactic latitude. It is very nearly face-on and has a recessional velocity of about 344 km/s. IC 4182 is the first galaxy for which the absolute magnitude of a type Ia Supernova has been determined empirically by tying to the Cepheid distance scale (Saha *et al*, 1994, ApJ 425, 14). In this lab we will be duplicating part of the detailed photometry the original researchers did. Our photometry work, if accurate enough, should reveal enough of a period for each star that we can calculate, from relationships derived from Cepheids in our local group, the distance to IC 4182 and thus the absolute magnitude of a type Ia supernova and from the distant supernovae the fate of the universe.

PROCEDURE

Your instructor will log you into one of the a200 accounts. Here we will assume you are the a200a user **BUT** each different terminal will be a different user a200b, a200c, ... to a200j, so you will need to substitute in the appropriate letter where ever you see a200a. An xterm should be present on the screen. By the way, the operating system, Unix, is case sensitive, so you will need to watch all keyboard input. Working inside the xterm, type:

/astro/a200>**pwd**

to confirm that you are in the directory /astro/a200a/. Type

/astro/a200>**cd ic4182**

followed by

/astro/a200>**ls**

to get a listing of all the files that we will use in this experiment.
Type

/astro/a200>**cd**

to go to your home directory.
Bring up the SAOimage and run it as a background task by typing

/astro/a200>**ds9 &**

IRAF

To use **IRAF** to display your images we need to change directories to the iraf directory, type

/astro/a200>**cd iraf**

Then to start iraf type

/astro/a200>**cl**

The screen will clear and the message of the day will appear.

Today we want to use some data gathered with the Hubble Space Telescope to measure the brightness of some Cepheid stars. Because the HST is above the Earth's atmosphere, the cosmic ray problem is very severe. Much of what looks like stars on the images are, in fact, cosmic rays. It is not very interesting to do photometry on cosmic rays, so we need to have a way to positively identify our target stars. We do this by placing one of the images in "background" or "blink" mode and then blinking subsequent frames against our reference frame.

To do this, follow these steps **EXACTLY**:

1. Type

cl> **cd ../ic4182**

to change directory up to the ic4182 directory

cl> **displ temp1 1**

This displays the image temp1 which is found in the directory a200a/ic4182.

2. Click on the button named "Zoom", and then "Zoom2".

This doubles the size of the displayed image.

This stores the image "temp1" in the first buffer.

3. Type **displ temp2 2**

This displays image temp2 in the second frame buffer, the one that you see now.

4. Use the [zoom] buttons to make this image the same size.

5. Make sure the cursor is in the image window. Now when you press the tab button, the first image will appear. By pressing the tab button you are actually displaying what you previously saved in the first buffer, in this case the image "temp1". You can blink the images back and forth by continuing to hit the tab key.

6. You can also make it blink the images by clicking on [frame] and [blink]. To stop, click on [single].

Since temp1 is the image used for the finder chart in your lab manual you should be able to locate the five stars and obtain their x and y coordinates. The stars will be in the same places on both frames and the cosmic rays will not be in the same places on both frames.

In general IRAF has many routines under its hierarchy of tasks to reduce data. You can find out which ones are available at any given level by typing **?** to find the names and then **help** *specifictaskname* to find out how to use them. Typing **epar** *specifictaskname* lets you edit some of the parameters of the routine. After the changes are made, **:wq** saves all changes or use **:go** to save the changes and execute the command.

The task *qphot* can be accessed by loading the packages *digiphot* and *apphot* by typing

cl> **digiphot**

and
di> **apphot**

Qphot requires certain parameters to be set such as whether to allow automatic centering or not, the size of the aperture for measuring the brightness of the star, and the size of the sky or background annulus over which to measure the sky.
ap > **epar centerpars**

to set the parameters for centering. The important parameter is the "cbox" which determines over what area the centering routine looks for the star and then centers the aperture on it. Type **:wq** when you are done.

```
                                 I R A F
                  Image Reduction and Analysis Facility
PACKAGE = apphot
   TASK = centerpars

(calgori=            centroid) Centering algorithm                 *
(cbox   =                  5.) Centering box width in scale units  *
(cthresh=                  1.) Centering threshold in sigma above background
(minsnra=                  1.) Minimum signal-to-noise ratio for  centering algo
(cmaxite=                  10) Maximum number of iterations for  centering algor
(maxshif=                  1.) Maximum center shift in scale units
(clean  =                  no) Symmetry clean before centering ?
(rclean =                  1.) Cleaning radius in scale units
(rclip  =                  2.) Clipping radius in scale units
(kclean =                  3.) Rejection limit in sigma
(mkcente=                  no) Mark the computed center on display ?
(mode   =                  ql)
```

ap > **epar fitskypars**

to set the parameters for finding the sky background light. The important parameters are "dannulus" and "annulus" which set the size of the annulus used for finding the background light. Even in orbit there is background light from the dust in the inner solar system which scatters sunlight into the telescope. Type **:wq** when you are done.

```
                                 I R A F
                  Image Reduction and Analysis Facility
PACKAGE = apphot
```

```
   TASK = fitskypars

(salgori=                mode) Sky fitting algorithm                      *
(annulus=                  5.) Inner radius of sky annulus in scale units *
(dannulu=                 7.5) Width of sky annulus in scale units        *
(skyvalu=                  0.) User sky value
(smaxite=                  10) Maximum number of sky fitting iterations
(sloclip=                 10.) Lower clipping factor in percent
(shiclip=                 10.) Upper clipping factor in percent
(snrejec=                  50) Maximum number of sky fitting rejection iteratio
(sloreje=                  3.) Lower K-sigma rejection limit in sky sigma
(shireje=                  3.) Upper K-sigma rejection limit in sky sigma
(khist  =                  3.) Half width of histogram in sky sigma
(binsize=                0.02) Binsize of histogram in sky sigma
(smooth =                  no) Boxcar smooth the histogram
(rgrow  =                  0.) Region growing radius in scale units
(mksky  =                  no) Mark sky annuli on the display
(mode   =                  ql)
```

Now it is time to identify the stars and write their x and y coordinates to file. The task *qphot* will read the stars' position from that file. An easy way to create a coordinate is to use the task *rimcursor*. Type

ap> **rimcursor temp1 > star.coo**

Once you have located a star, put the cursor at the center of that star and press "space bar". This action will write the x and y coordinates of the cursor to the file "star.coo".

When you are done, make sure the cursor is in the DS9 window then type **Crtl-Z**.

Check to see that the file star.coo has sensible numbers in it with:

ap> **cat star.coo**

ap > **epar qphot**

to set the parameters for finding the brightness of the star. The important parameters are the "aperture" which is the diameter of the area used to find the star's brightness and the "annulus" and "dannulus" which is the area used to find the brightness of the sky. The "zmag" is the zeropoint of the magnitudes and is set by observing standard stars with the same telescope and filter etc.

```
                              I R A F
                    Image Reduction and Analysis Facility
PACKAGE = apphot
   TASK = qphot

image   =               temp*  The input image(s)
cbox    =                  1.  The centering box width in pixels
annulus =                  5.  The inner radius of sky annulus in pixels
dannulus=                 7.5  The width of the sky annulus in pixels
aperture=                 2.5  The list of photometry apertures
(coords =           star.coo) The input coordinate file(s) (default: *.coo.?)
(output =            default) The output photometry file(s) (default: *.mag.?)
(plotfil=                   ) The output plot metacode file
(zmag   =               21.3) The zero point of the magnitude scale
(exposur=            EXPTIME) The exposure time image header keyword
(airmass=                   ) The airmass image header keyword
(filter =                   ) The filter image header keyword
(obstime=           EXPSTART) The time of observation image header keyword
(epadu  =                 8.) The instrument gain in e-/ADU
(interac=                 no) Interactive mode ?
(radplot=                 no) Plot the radial profiles in interactive mode ?
(icomman=                   ) Image cursor: [x y wcs] key [cmd]
(gcomman=                   ) Graphics cursor: [x y wcs] key [cmd]
(wcsin  =          )_.wcsin) The input coordinate system (logical,tv,physical
(wcsout =         )_.wcsout) The output coordinate system (logical,tv,physica
(cache  =          )_.cache) Cache input image pixels in memory ?
(verbose=                 no) Print messages in  non-interactive mode ?
(graphic=           stdgraph) Graphics device
(display=           stdimage) Display device
(mode   =                 ql)
```

To start doing the photometry, type **:go**. This will take a few moments as the program as to do a series of calculations for each of the five stars 20 times (there are 20 images).

Then type **ls** to see what files you have made and then **cat temp2.mag.1** to zoom through one of the files you have created.

Make sure the photometry files are all the same size using:

ap > **ls -l *mag***

Then to extract just the magnitudes and the times of observation:

ap > **pdump t*mag.1 "otime,mag" "id=1"**

to see the magnitudes and times on the screen. To get back the last commands that IRAF executed type an up arrow and the down arrow to scroll through the commands. This very handy when you want to see some data on the screen and then to save the same data to a file. Use the up arrow command and then edit it to be:

ap > **pdump t*mag.1 "otime,mag" "id=1" > star1**

to save the times and magnitudes in a file called star1.

The quotation marks are needed. Repeat for other stars changing the **id=1** and **star1** to **id=2 star2** to make another file with star2's values. et cetera

You now need to sort the data chronologically. Column 1 contains the date of the observations. The task *sort* can help you. Type

ap > **sort star1 col=1 > star1.sort**

Repeat for the 4 other files : star2, star3, star4, and star5.

You now want to graph your results. We will use the application *Xmgr*. To start it, type

ap > **!xmgr &**

Select "File", then the option "Read" then "Sets". Select the file "star1.sort" and press the button "Ok' **ONLY ONCE**. Then press "Cancel". Click on the autoscale button "AS" located below "Draw". You should now see the light curve. Double-click above the plot; enter the title. Double-click on the left and write the y-axis label. Double-click below the plot and enter the x-axis label. The x-axis is the Julian Date (actually 2400000 + the date shown) and the y-axis is the star's apparent magnitude. The title should include the number of the Cepheid that you are doing.

We will now invert the y axis so that the brighter the star the higher it is on the plot. Press on "Data" and select "Graph Operation" then "Invert/Flip Axes" then select the button "Invert Y".

We are now ready to print the plot. In the "File" section, select the option "Print".

To clear the current plot go in "Data" and select "Set operation". There you will find the option "Kill all"; click on it. The data set will go away but the axis label will stay saving you some time.

Create a similar plot for the other stars. Don't forget to change the title.

DETERMINING THE DISTANCE TO IC 4182

Your plots may not make any sense initially because there may be cosmic rays which landed on a star affecting your results. This will make one point far too bright. The Cepheids will have a period of 3 to 30 days and an amplitude of about one magnitude. The stars brighten more quickly than they become fainter. See if you can recognize the underlying variability of the star and calculate a period. The period is simply the difference in the Julian Dates, which may be accurate down to a fraction of a day.

Then find the distance to each Cepheid using the relationships:

$$M_v = -2.88 \log P - 1.24$$

and

$$m_v - M_v = 5 \log D - 5$$

where M_v is the absolute magnitude, P is the period in days, m_v is the apparent magnitude, and D is the distance in parsecs. Find the mean distance and its standard deviation and the error in the mean.

Compare your derived value with that obtained from the original work $4.7 \pm .2$Mpc.

A really great website for Cepheids is:

http://dogwood.physics.mcmaster.ca/

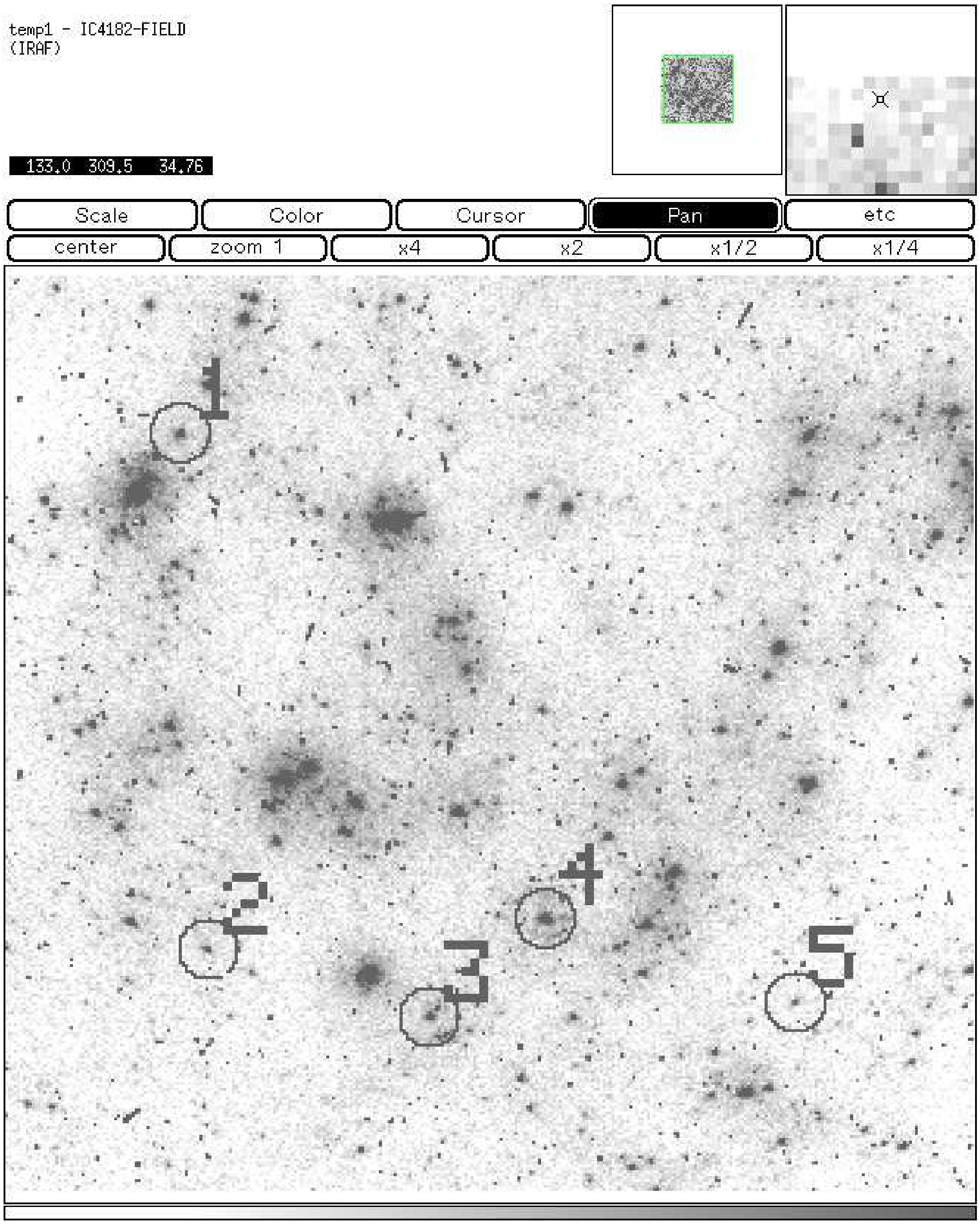

Figure 12.1: Finder chart for five Cepheids in IC4182

13 THE HUBBLE PARAMETER

The Hubble parameter (often called the Hubble Constant) is the relation between the distance and velocity observed for distant galaxies. This relation is strong evidence that there was a Big Bang at sometime in the past. How far in the past can be found from the Hubble parameter. The velocity is relatively easily found from spectra of the galaxy. The distance to a galaxy is much more difficult to find. Generally astronomers use the observation that "small means far" or "faint means far" to find the distance to a galaxy.

The Angular-Diameter - Redshift Relation

In the table is a list of Sb spirals that are judged to be "similar" on the basis of appearance. Notice that Andromeda Galaxy (M31) (NGC 224) is an Sb spiral that is judged to be similar to the other objects.

The whole sky has been photographed using the Palomar Observatory telescope and these prints are called the Palomar Observatory Sky Survey or POSS. The original photographs have been scanned and we can look at them with the program **skycat**.

Measure the angular diameter of each object on the POSS prints. (Your instructor will explain how to find the objects.) What are some uncertainties in your measurements? Comment on the appearance of each object compared to M31.

Object	α 1950	δ1950	Vel. (km/s)	B_{oT}
NGC 224	00h40m0	+41 00	-10	2.71
615	01 32.6	-07 36	1971	11.39
779	01 57.2	-06 12	1492	10.80
2815	09 14.1	-23 26	2333	11.34
5005	13 08.6	+37 19	1042	9.81
2841	09 18.6	+51 11	714	9.24
3521	11 03.3	+00 14	627	8.84
4814	12 53.2	+58 37	2650	12.21

Assuming that each object possesses the same physical diameter, calculate the distance to each object. (Assume that d(M31) = 900 kpc. Hipparcos 1997)

Plot Vo vs. distance with XMGR

To do this we can use the simplest UNIX editor, pico, to type in the data. The lab instructor will sign you on and all you need to do is change directory to the "**Hnot**" directory if you are not already there with:

$/astro/a200>$**cd Hnot**

$/astro/a200>$**ls**

will list the files and you should see

```
ellipticals    spirals    spirals.mag    images
```

or something similar. These files must be there and the other files are left over from the last student to use the directory. You can delete them or leave them.

$/astro/a200>$**cd images**

Start skycat with:

$/astro/a200>$**skycat**

Measure the galaxies by dragging the right hand button across the galaxy from one side to the other and reading the number on the hypotenuse. Since the galaxy fades into the sky you may need to think/experiment with this.

Record your diameters with the editor pico and run it in the xterm window.

Start **pico** with:

$/astro/a200>$**pico**

and just type in your values for the velocity and the distance with a space or two in between and each pair on a different line. Use the arrow keys to move around in the file. When you are done type a "**[crtl] x**" and save the file with a new name.

To plot the file we want to use the program "xmgr" which we can start with:

$/astro/a200>$**xmgr &**

This will spawn a new window, which you can paste with the left mouse button. This is a mouse based program so double click on the center of the graph area and a "**read sets**" window will open. Type the name of your file in the "**Selection**" box and click on **OK - only once**. Click on **AS** to "Autoscale" the data. Click the left button on "**Plot**" and choose **Symbols...**. Change "symbol" to "Circle" and "Filled" and "Line properties" to "None". Click on "Accept" and the graph will look nicer. I hope.

Linear Least Square Fit

The XMGR program can also fit functions to the data. Let's fit a straight line to our data. Click on **Data**, **Transformations** and **Regression**. In the "Regression" window click on "S0", which means "set zero" and check to make sure the "Type of fit" is "Linear". Click on **Accept** and the "Results" window will appear.

What is the "SLOPE" of your data? Compare with usual values of $H_o =$ 50 to 100 km/sec/Mpc . What is the meaning of the "INTERCEPT" How can this relation be used to determine the distances of galaxies? To save these values you can click on **Save**, type a file name in the box, and click on **Accept**.

To add a title to your graph just double click on the area above the top axis and a new window will appear. To add axis labels just double click on the side of the graph outside the plotting area.

To make a hard copy of the graph click on **File** and **Print**. Once you have collected your printout, then clear the set of points out of "XMGR" by clicking on **File** and **Clear all**.

The Magnitude-Redshift Diagram of Spirals

Make a plot of B_{oT} ("corrected total apparent blue magnitude") against $\log V_o$ for the galaxies listed above. Do not plot M31 for now.) The data has been enter into the file "spirals.mag" and you can look at this file with pico or by typing:

$/astro/a200$ >**cat spirals.mag**

Use "XMGR" to plot this data using the same commands as you used in the first part. "XMGR" has routines for changing the data. Read the data set into XMGR as before and then click on **Data, Transformations** and **Evaluate Expression**. This window will let you change all your x's to $\log x$ by typing

$x = log10(x)$

into the "Formula" box and then clicking on the **Accept** button.

Then click on **Regression** and find the "SLOPE" and "INTERCEPT" and their errors.

Assume that all of the plotted galaxies possess constant absolute B magnitude M_B. Derive a theoretical relation between apparent magnitude B and $\log V_o$. The Hubble Law is:

$V_o = H_o D$

where D is the distance measured in Megaparsecs. What is $\log V_o$ equal to?

Remember that the absolute magnitude is related to the apparent magnitude by:

$B - M_B = 5 \log D - 5$

where D is in parsecs. We want D in megaparsecs so how will this equation change? So combine the equations and arrange them for B as a function of $\log V_o$. How does the predicted slope of this relation agree with the slope that you measured above?

Using d = 900 kpc for M31, calculate M_B(M31). If this is also the M_B value for other galaxies in your sample, what is the Hubble constant H_o? (Hint: measure the intercept of your $B - \log V_o$ plot.) How does your value agree with the earlier determination of H_o?

Find the velocity that M31 should have if it obeyed the Hubble Law. Why does M31 not obey the Hubble Law?

Note: the magnitude-redshift diagram is also called the "Hubble Diagram". From the slope of this plot, Hubble first inferred the existence of the relation $V \propto D$ in the late 1920s. You may read his original paper in Astrophys. Journal, vol. 74, p. 43 (1931); the library has this volume.

Magnitude-Redshift Diagram ("Hubble Diagram") of Distant Elliptical Galaxies

In the file "ellipticals" is a compilation of some of the available data on the brightest galaxies in rich clusters of galaxies, taken from Kristian, Sandage and Westphal (Astrophys. Journal), vol. 221, p. 383 [1978]). From some of these data make a plot of $V_C^{R,BM}$ $(q_o = 0)$ magnitude versus $\log z$, where z = redshift.

$$z = \frac{\Delta\lambda}{\lambda} \simeq \frac{V}{c} \tag{13.1}$$

Use least squares techniques to find the slope of this plot; comment. The dispersion of brightest cluster galaxy about the line can be found from the "Results" window in the "Analysis of variance" section the "Mean Square" "Residual". The square root gives the Root Mean Square which is the average distance of the point from the line in the y direction. What can you conclude about the uniformity of the brightness of brightest cluster galaxies?

The nearest big cluster of galaxies is the Virgo cluster and the second brightest cluster member is M87. The total apparent V magnitude of M87 is +8.7 and its distance is 16.5 Megaparsecs. What is the absolute V magnitude of M87 and compare this to the Andromeda galaxy.

Derive a value of the Hubble constant from the intercept of your magnitude red shift diagram. Compare your previous measurements of the Hubble constant and comment.

Questions

1. From the radial velocity and distance to a galaxy we can calculate the time it would take that galaxy to get to that distance. This is the length of time since the Big Bang. The Hubble parameter is just the reciprocal of this time in unusual units. Find the age of the Universe.

2. Since every mass in the universe attracts every other mass, the expansion should be slowing. Explain qualitatively what you would expect to see in the most distant object's velocities.

14 THE TULLY-FISHER RELATION

OBJECTIVE

To investigate the relation between the rotation velocity and the intrinsic brightness of a galaxy; to determine the distance modulus to the Virgo cluster and derive a value for H_o.

INTRODUCTION

In 1977 Brent Tully and Richard Fisher discovered a correlation between the absolute blue magnitude of a spiral galaxy (its luminosity) and the rotational velocity as measured by the width of the radio emission line at 21 cm due to neutral atomic hydrogen. With large radio telescopes, the 21 cm line is readily observable in distant galaxies. Tully and Fisher used this information to calibrate the distances of galaxies which were located well beyond the limitations of previous distance indicators.

This correlation makes physical sense. The more massive the galaxy is then the faster the stars of the edge of the galaxy will move in their orbit. Balancing the gravitational and centrifugal forces gives us:

$V = \sqrt{GM/R}$

Where V is a star's velocity, G is the gravitational constant, M is the mass of the galaxy and R is the radius of the star's orbit. The more massive a galaxy then the larger the luminosity L we would expect it to have.

$L \propto M$

The brightness of the galaxy is also proportional to the area of the disk.

$L \propto R^2$

From these relations show that the relation of luminosity to velocity is:

$L \propto V^4$

Question:

Express this relationship in magnitudes as a function of $log_{10}V$.

The original Tully-Fisher work suffered some serious drawbacks, however, as a number of significant corrections needed to made to the observables. The most critical correction was for internal absorption, which affects the blue magnitudes more than the infrared. You must remember that spiral galaxies contain a great deal of dust and the absorption from this dust is greatest when the galaxy is seen edge on because the dust tends to congregate along the plane of the galaxy. The inclination angle of the galaxy also affects the value of the measured 21 cm profile width (W) and a correction must be made for this to get the maximum rotation velocity (V) in disk galaxies.

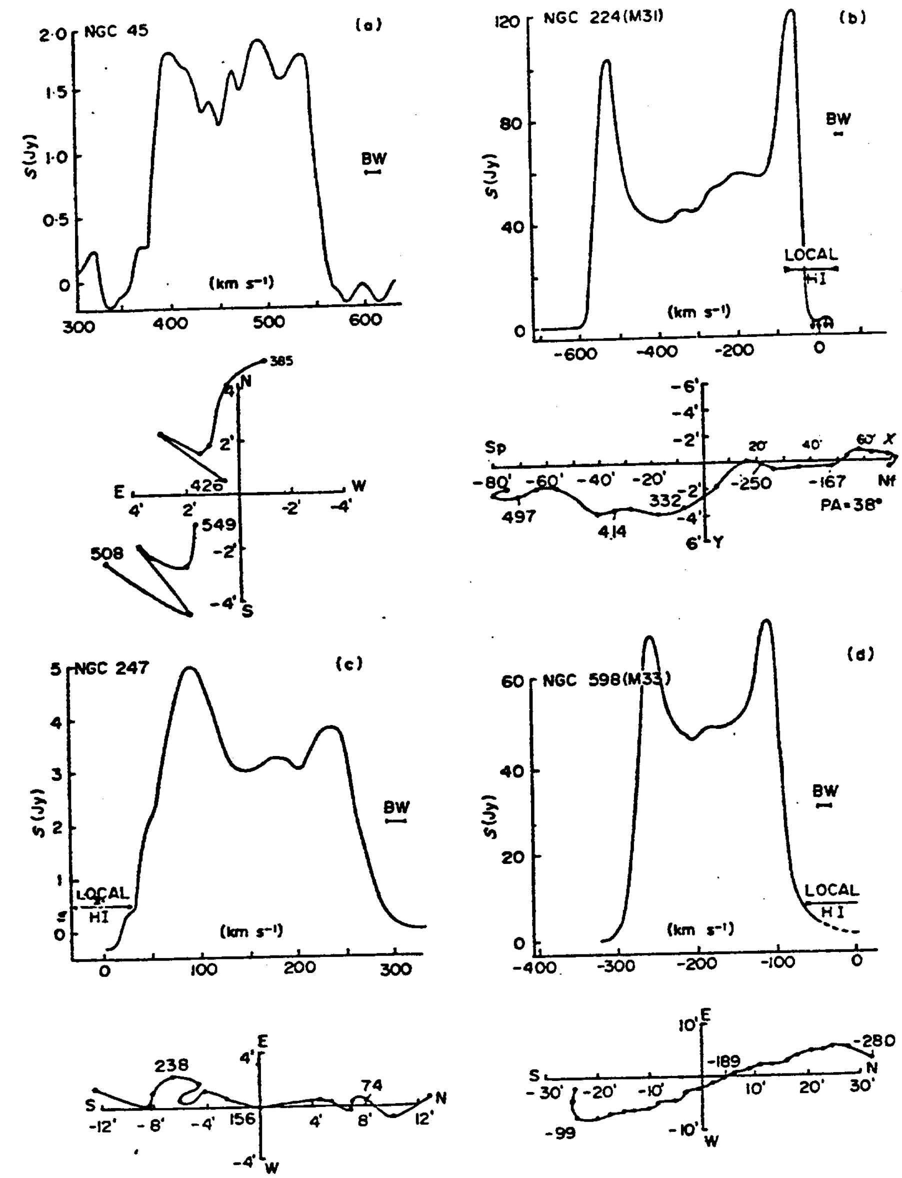

Figure 14.1: The HI profiles of the Spiral Galaxies M31 and M33.

Sketch an edge-on spiral galaxy and indicate where each part of the HI profile originates; i.e. place the double-horned profile under your sketch at the appropriate scale.

Local Calibrators

The calibration for this relation that we will use is the absolute infrared M_H (1.6μm) magnitudes and velocity width data for local galaxies, for which distances are available from a variety of other techniques.

Object	m_H	Inclination	Distance	$W_{obs} \frac{km}{sec}$
M31	0.91	78^o	.77Mpc	-
M33	4.38	57^o	.843Mpc	-
M81	4.38	57^o	3.6Mpc	400
NGC300	6.87	43^o	2.1Mpc	186
NGC925	8.74	57^o	9.3Mpc	214
NGC1365	7.20	48^o	18.2Mpc	483
NGC2366	10.82	69^o	3.4Mpc	77
NGC2403	6.47	59^o	3.2Mpc	245
NGC3109	7.00	80^o	1.3Mpc	120
NGC4536	8.30	70^o	16.6Mpc	308

Complete the table by finding the velocity width W_{20}^{obs} (measured at 20% peak intensity) for M31 and M33 from the spatially integrated H I spectra given in Figure 14.1. The inclination is defined as the angle between the celestial sphere and the plane of the galaxy. An edge-on galaxy will have an inclination of 90^o. It usually found from the axial ratio of the galaxy. Then correct ALL W_{20}^{obs} values for the inclination effects to get the W's. You will also need to use the apparent magnitude m_H and the given distances (in units of parsecs) to derive the absolute H magnitudes, M_H using the distance modulus formula:

$m_H - M_H = 5 \times log_{10}D - 5.$

For these local group galaxies, we want to plot absolute magnitude M_H against $log_{10}W$. Then we want to derive the constants "a" (intercept) and "b" (slope) using linear least-squares fit for a line of the form

$M_H = a + b \times logW_{20}^{i=90}$

that passes through the data points.

Editing the Data

Your instructor will log you into one of the a200 accounts. The operating system we use is UNIX and we will use the XMGR data reduction program. If you type in **ls** , you will see a listing of the files and sub-directories present in the directory you are in.

/astro/a200> **cd hubble**

Type

/astro/a200/hubble> **ls**

to see what files reside in this directory. One of the files is called fishtul.vrg and contains the data for the next section. To see this file on the screen type:

/astro/a200/hubble> **cat fishtul.vrg**

The file contains the apparent the $log_{10}W$ and the apparent H magnitudes for the spiral galaxies in the Virgo cluster. We want to create another file just like it for the local calibrator spiral galaxies only we will use the absolute H magnitudes. To use UNIX's simplest editor type:

/astro/a200/hubble> **pico local**

to make a file called local. Then type in two columns the $log_{10}width$ and the absolute magnitude in the H band for the calibrating galaxies. When you are finished typing in your values you exit pico with a ctrl x.

Plotting

Next we want to plot a graph of these values to see if the rotational velocity is really related to the brightness of a galaxy. To start XMGR type:

/astro/a200/hubble> **xmgr &**

Double clicking on the center of the graph area will bring up a "Read Sets" window into which you can type your filename. Then click bf only once on "OK" and then click on "cancel" to get rid of this window. Click the left mouse button on the button marked"AS" and xmgr will auto-scale your data. Click on "Graph" and "Symbols" to set the symbol to circle and filled and to set the "Line properties" to None. Click Accept to see the graph points appear.

Polynomial Fitting

Hopefully you will see that there is a linear relation between the rotational velocity and the intrinsic brightness of the galaxies. We can find the slope and intercept of this relation using the “Regression” task in XMGR.

Click on “Data” and “Transformations” and “Regression” to get the Regression window. Select the “S0” set and check to see it is a Linear fit and then click on Accept to see the “Results” window appear.

XMGR will output the intercept, the slope, and the errors in each. Also listed are various statistics related to the goodness of the fit and the Mean Square Residual, which is the square of the average deviation of a point from the line. This quantity is what tells us how well your line can predict the y value. Record these values in your book or save them to a file and print them later.

Title and label the plot by double clicking on the area above the graph and to the side of it where the labels should go. Print the graph on the printer by clicking on “File” and “Print”.

Virgo Cluster Spiral Galaxies

Plot the apparent H magnitude - log W diagram for the galaxies in the Virgo Cluster. The data is in the file “fishtul.vrg”. Use XMGR’s regression function to find the slope, intercept and standard deviation residual and compare them to what you found from the local calibrator spirals.

You can set the limits of the plot by clicking on “Graph” and “World Scaling”. You can change the “Xmin” and “Xmax” to the same values you used for the Local Calibrators plot. Then you can print it out.

The galaxies in the Virgo cluster are all at about the same distance. We know this because if some of the galaxies were in the background they would not lie on the relationship. We can find the distance to the Virgo cluster by finding the apparent H magnitude of a spiral galaxy in the Virgo cluster and finding the absolute H magnitude of a spiral galaxy from the local calibrators, which is the same size. These magnitudes can be found from the lines fit by the linear regression routine given typical values of the rotation velocity. Choose a couple of different rotation velocities to get a couple of different magnitudes, to help estimate the uncertainty. The distance modulus equation will then give the distance to the Virgo cluster.

If the Recessional Velocity of the Virgo Cluster is 1200km/sec calculate the Hubble parameter.

Questions

1. Explain whether you would expect an elliptical galaxy to fit your Magnitude-Velocity relation.

15 FIELD TRIP TO THE DAO

OBJECTIVE

Since the University of Victoria is fortunate to have the Dominion Astrophysical Observatory (DAO) nearby, we will make a field trip to see the facility. We want you to write a few pages about what you learn on the trip.

INTRODUCTION

The Observatory is composed of two telescopes, about a hundred astronomers and support staff, and offices, shops and a library. The Observatory awards time on its telescopes based on a competition among astronomers from across Canada and the rest of the world. Tonight's observers have kindly agreed to let us visit the telescopes, while they are making measurements.

The telescopes are the 1.8 meter (72-inch) and 1.2 meter (48-inch). These telescopes are generally used with spectrographs, but occasionally are used with cameras to take images of the sky. CCD low-light-level TV cameras are generally used to detect the light. The objects observed are usually stars, galaxies, asteroids, planets, quasars or nebulae. The reasons for observing the objects are as diverse as the objects themselves.

What we see on your particular night will depend on the night. If it is clear and the astronomers are working, we will not be allowed to turn-off the detectors and see the inside of the spectrographs. However we probably will see "real" data coming up on the screen. We will see the telescopes move and the dome rotate. The displays downstairs in the 72 inch are also very interesting. Dress warmly and if it is raining bring your umbrella.

EXERCISES

1. Sketch the telescopes and show the light path from the front of the telescope to the detector. Include the mounts of the telescopes in your sketches. Describe each of the components on the telescopes and give the function of each component.

2. Contrast the type(s) of focus used on the 72" with that of one of UVic telescopes that you have used. What are the advantages and disadvantages of each?

3. Compare these telescopes to the ones you have used at UVic. You may wish to consider in your discussion the types of detectors used, the light gathering capability, the different mounts.

4. What are each of the observers observing? Why are they observing it? How will the data be reduced? Where will it be published?

5. If this is not your first trip to the DAO with an astronomy class, and you have sketched the telescopes before, instead of doing numbers 1 and 2 of this exercise please do the following: Write a 2 or 3 page essay about an interesting astronomical question. One idea is to use what the observers at the DAO are observing. Another good place to get ideas is to look at "Sky and Telescope" magazine.

6. The DAO websites are located at:

`http://www.nrc-cnrc.gc.ca/eng/ibp/hia.html`

`https://www.astrosci.ca/DAO/skycam.html`

A COMMON LINUX COMMANDS

Linux runs differently from other operating systems you have probably used before. To use Linux, you usually type commands into a *terminal*. Table A.1 shows common commands that you will have to use in A250. The symbol > shows the terminal line; you type in everything after that.

Table A.1: Common Linux commands.

Command	**Function**	**Example**
`cd`	Changes directories (type it by itself to return to the home directory)	`> cd a200/`
`ls`	Lists files and subdirectories in the current directory	`> ls`
`mv`	Moves files to a new directory	`> mv file1 folder/`
`pwd`	Checks which directory you are in	`> pwd`
`*`	A wildcard that will stand in for all symbols	`> ls *.fits` will list all the .fits files
`cl`	Opens IRAF (use in an xgterm window) (Note: you'll need to cd to /iraf/)	`> cl`
`ds9`	Opens DS9 (to view/edit images)	`> ds9 &`
`gedit`	Opens a text editor	`> gedit` *filename* `&`
`xgterm`	Opens an xg terminal	`> xgterm &`

B IRAF RESOURCES

The Image Reduction and Analysis Facility (IRAF)[5] is commonly used in astronomy to view, edit, etc. data, particularly CCD images. Commands or parameters that are specific to a lab will be discussed in the lab. Here we summarize the main commands and quirks of IRAF.

IRAF has already been installed/initialized on your machines. It is optimized to be run in a special terminal called an `xgterm`. You'll need to open an xgterm (see Appendix A), `cd` to `/iraf/`, and then start IRAF by typing `> cl`. The following provides a brief description of how IRAF works.

Packages: IRAF uses tools that are included in separate packages. It does not load all its packages at the beginning. Instead, you must tell it which packages you wish to use. To load the package, simply type its name. For example, suppose you wish to load the `imred` (image reduction) package. You simply type `> imred` into the terminal.

Tasks: The tools that do the bulk of the work are known as tasks. Once you have loaded the necessary packages, you execute a task by typing its name. For suppose, suppose you wish to plot a spectrum. You load the `imred` and `specred` packages, and then type `> splot`. IRAF will then ask you what spectrum (.fits file) you want to plot.

Task Parameters: The tasks have different parameters, which may need to be changed from the default values (depending on what you are doing). If you need to change the default values, the lab will tell you which ones to change.

To change the values for a specific task, you type `epar` *task name*. You can then use the arrow keys to navigate to the parameters that need to be changed, and type in the new values.

There are some commands that are used fairly often; they are shown in Table B.1.

[5]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table B.1: Common IRAF commands.

Command	**Function**	**Example**
`epar`	Shows the parameters for a particular task, allows them to be changed	`> epar` *task name*
`cat`	Displays the contents of a file (useful for viewing text files in IRAF)	`> cat` *filename*
`dir`	Lists all the files in the current directory (similar to `ls`)	`> dir`
`display`	Displays a fits image in DS9	`> display` *filename*
`go`	Stars a task running (from within the parameter file)	`> :go`
`imhead`	Displays image header information for a fits file	`> imhead` *filename*
`unlearn`	Restores parameters to default values	`> unlearn` *filename*
`logout`	Quits IRAF	`> logout`